VIRGINIA DIVISION OF MINERAL RESOURCES
PUBLICATION 119

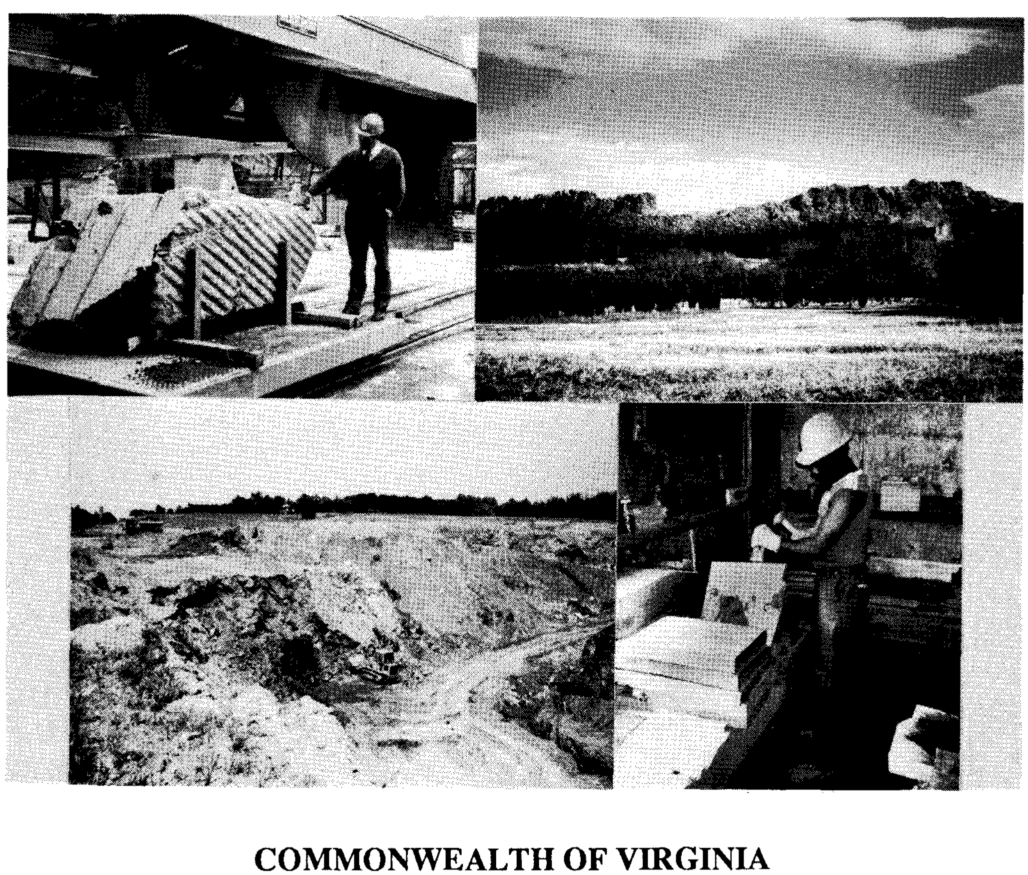
PROCEEDINGS

26TH
FORUM ON THE GEOLOGY OF INDUSTRIAL MINERALS

May 14-18, 1990

Edited by

Palmer C. Sweet



COMMONWEALTH OF VIRGINIA

DEPARTMENT OF MINES, MINERALS AND ENERGY
DIVISION OF MINERAL RESOURCES

CHARLOTTESVILLE, VA
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RICHMOND, VIRGINIA
O. Gene Dishner, Director

FRONT COVER: Sites and activities at the quarry operations visited during the 26th Forum on the Geology of Industrial Minerals, May 14-18, 1990, Charlottesville, Virginia. Upper left photograph, clockwise: sawing soapstone at The New Alberene Stone Company, Schuyler, Nelson County; kyanite-bearing quartzite ridge of Willis Mountain, view to north-northeast, Kyanite Mining Corporation, Dillwyn, Buckingham County; producing slate shingles at LeSueur Richmond Slate Corporation, Arvonia, Buckingham County; mining vermiculite from open pit at Virginia Vermiculite, Ltd., Louisa County (Photographs by William F. Giannini, David A. Hubbard, Jr., and Palmer C. Sweet).

Printing jointly funded by the Commonwealth of Virginia and the 26th Forum on the Geology of Industrial Minerals.

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CHARLOTTESVILLE, VA
1992

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ANNUAL MEETINGS

FORUM ON THE GEOLOGY OF INDUSTRIAL MINERALS

1st	1965	Columbus, Ohio
2nd	1966	Bloomington, Indiana
3rd	1967	Lawrence, Kansas
4th	1968	Austin, Texas
5th	1969	Harrisburg, Pennsylvania
6th	1970	Ann Arbor, Michigan
7th	1971	Tampa, Florida
8th	1972	Iowa City, Iowa
9th	1973	Paducah, Kentucky
10th	1974	Columbus, Ohio
11th	1975	Kalispell, Montana
12th	1976	Atlanta, Georgia
13th	1977	Norman, Oklahoma
14th	1978	Albany, New York
15th	1979	Golden, Colorado
16th	1980	St. Louis, Missouri
17th	1981	Albuquerque, New Mexico
18th	1982	Bloomington, Indiana
19th	1983	Toronto, Ontario
20th	1984	Baltimore, Maryland
21st	1985	Tucson, Arizona
22nd	1986	Little Rock, Arkansas
23rd	1987	North Aurora, Illinois
24th	1988	Greenville, South Carolina
25th	1989	Portland, Oregon
26th	1990	**Charlottesville, Virginia**

FOREWORD

The 26th Forum on the Geology of Industrial Minerals was held May 14-18, 1990 in Charlottesville, Virginia. The forum was sponsored by the Virginia Division of Mineral Resources, Department of Mines, Minerals and Energy. The meeting consisted of 3 days of technical sessions and 2 days of field trips to dimension slate and soapstone operations, the only domestic kyanite producer and a vermiculite operation. Two excursions to Natural Bridge and to view dinosaur footprints in Mesozoic age sediments as well as 3 separate spouse events were provided. A total of 200 registered for the meeting.

The meeting was kicked off with a panel consisting of government personnel from the State of Virginia, U.S. Bureau of Mines and U.S. Geological Survey. They presented their agency's role in industrial minerals and then fielded questions from the audience. Presentations during the technical sessions consisted of papers on aggregates, brucite, carbonates, clay, dimension stone, high-silica resources, karst deposits, kyanite, pegmatites, slate, soapstone, and vermiculite. Papers on the use of computers to compile and disseminate resource data, aid in computing reserves, developing a mining plan and planning a reclamation program were also presented. Additional presentations were given on the role of regulatory agencies with the mining industry and the image of the mining industry.

Financial support for the meeting was received from LeSueur Richmond Slate Corporation, Luck Stone Corporation, North American Exploration, Inc., Virginia Vermiculite, Ltd. and W.W. Boxley Company as well as from the Society of Economic Geologist's Foundation, Inc.

This proceedings volume contains papers and abstracts of presentations at the forum. Only a "light" edit has been done on the papers submitted for this proceedings volume.

Palmer C. Sweet

CONTENTS

PAPERS

ABSTRACTS

INDUSTRIAL ROCK AND MINERAL PRODUCTION IN VIRGINIA

Palmer C. Sweet
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P. O. Box 3667
Charlottesville, Virginia 22903.

ABSTRACT

Industrial rock and mineral production in Virginia in 1989 was 520 million dollars from five physiographic provinces: the Coastal Plain, Piedmont, Blue Ridge, Valley and Ridge and the Appalachian Plateaus. This production represents a 12.5 percent increase over the 1987 figure of 461 million dollars and more than a five percent increase over the 1988 figure of 494 million dollars. Stone represents 66.9 percent of the total of 520 million dollars of production, while sand and gravel and lime represent 9.2 and 7.4 percent respectively (Figure 1). Much of the increase in production is due to the additional taxes initiated in Virginia in 1986 to increase funding for highways, airports, ports and mass transit.

Production of industrial rocks and minerals and products in Virginia includes masonry and portland cement, clay materials, construction sand and gravel, crushed stone, dimension stone, feldspar, gem stones, gypsum, industrial sand, iron-oxide pigments, kyanite, lime and vermiculite.

Industrial rocks and minerals, imported from out of state and processed in Virginia, include calcium aluminate cement, gypsum, iron-oxide pigments, lithium hydroxide, mica, perlite, and phosphate rock. Industrial sulfur is produced from the refining of imported crude oil at the Amoco Oil Company in Yorktown.

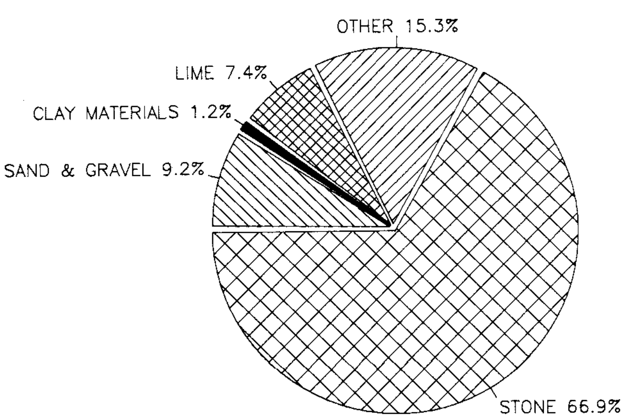


Figure 1. Virginia industrial mineral production - 1989; OTHER includes absorbent clay, feldspar, industrial sand, iron-oxide pigments, gypsum, kyanite, and vermiculite.

INTRODUCTION

Industrial rocks and minerals and products, produced and processed in Virginia accounted for a record 520 million dollars in 1989. When compared with 1988, values for lime increased more than fourteen percent and the value of crushed stone was up almost six percent. Production (tonnage) of crushed stone for 1989 over 1986 figures indicates a 27.5 percent increase. The increased crushed stone production is mainly due to the additional taxes initiated in Virginia in 1986 to increase funding for highways, airports, ports and mass transit. Additional tax dollars are being raised by increased state tax on gasoline by 2.5 percent, by increased automobile titling tax by 1.0 percent, increased state tax by 0.5 percent and the increased state tax on aviation fuel by one cent per gallon. Eighty five percent of the increased revenue ($400+ million per year) will be utilized in upgrading and building new roads in the state. An additional approximate $200 million per year of federal funds will also be utilized in this increased road building effort in the 1990s.

INDUSTRIAL ROCKS AND MINERALS AND PRODUCTS PRODUCED IN VIRGINIA

CEMENT

Two companies, in Warren and Botetourt Counties, produce cement in Virginia. Riverton Corporation in Warren County produces masonry cement at their plant north of Front Royal. Crushed limestone (Edinburg Formation) is calcined, hydrated, and mixed with portland cement from out-of-state sources. Sales are made to building supply dealers in Virginia and surrounding states. Roanoke Cement Company operates a plant in western Botetourt County. The facility manufactures portland cement from locally mined limestone, shale, and iron scale from Roanoke Electric Steel Company. Clinker is manufactured in five coal-fired kilns and ground into cement. Three-fourths of the cement is sold to ready-mix companies.

CLAY MATERIALS

Residual and transported clay, weathered phyllites and schists, and shale are used as raw material to produce almost one-half billion bricks in Virginia annually, when all the plants in the state are working at full capacity. The clay-material industry in the western part of the state mines Paleozoic age shales, with the primary end-products being common and face brick. Face-brick producers in the central-eastern part of Virginia mine Triassic age shale and clay residuum in Orange and Prince William Counties and Precambrian age schists, residual clay and transported clays in Amherst, Brunswick, Chesterfield, Greensville, and Henrico Counties.

Lightweight aggregate is produced in Botetourt, Buckingham, and Pittsylvania Counties. Weblite Corporation in Botetourt County mines shale from the Rome Formation to produce lightweight aggregate by the sintering process, using semi-anthracite waste coal from Montgomery County to fire the kilns. They utilize about 100 tons of coal per day to yield a lightweight-product having a weight as low as 31 lb/ft^3 for 5/16 to 3/4 inch particle sizes. Solite Corporation in northern Buckingham County uses the Arvonia Slate of Ordovician age to produce lightweight aggregate. Triassic age shale is used by Virginia Solite Company southwest of Danville, Pittsylvania County, to obtain a similar product.

Clay from the Cold Spring kaolin deposit in southeastern Augusta County is intermittently utilized by James River Limestone Company, Inc. to mix with the crushed dolomite at their operation near Buchanan, Botetourt County to produce various grades of filler material and as an ingredient in white cement.

Bennett Mineral Company in the Walkerton area of King and Queen County in eastern Virginia mines and processes montmorillonite clay to produce an industrial and sanitary absorbent. The facility uses wood wastes as a plant fuel to dry the clay in a rotary kiln.

CONSTRUCTION SAND AND GRAVEL

Construction sand and gravel producers accounted for the majority of the 12.5 million tons of material produced in 1989. Sand and gravel is extracted from the terraces and dredged from the rivers of the major drainages in central and eastern Virginia (Figure 2). Large tonnages of construction sand and gravel, from southeast of Fredericksburg, are shipped by rail into the northern Virginia-Washington, D.C., market area. A large portion of the production by Sadler Materials Corporation and Tarmac Virginia, Inc. near Richmond is barged down the James River to the Norfolk area. Shipments are also made by rail and truck to the western part of the state. Construction sand (concrete and masonry) is also produced from operations that crush and process sandstone. Sayers Sand Company in Smyth County produces construction sand from the Erwin Formation.

CRUSHED STONE

Crushed limestone, dolomite, sandstone, quartzite, granite, gneiss, diabase, basalt, greenstone, amphibolite, slate, "Virginia aplite," and marble, valued at more than 344 million dollars was produced in Virginia in 1989 (Figure 3). The previous year, Virginia was the fourth leading producer of crushed stone behind Pennsylvania, Florida and Texas.

Limestone, dolomite, shale, and sandstone and quartzite mineral producers are located in the Valley and Ridge and Plateau provinces in the western portion of the state. Principal end uses were for roadstone, concrete aggregate, asphalt stone, and agricultural application. Mine safety dust (335,000 short tons in 1980) is produced in southwest Virginia from limestone. More recent figures on safety dust are combined with those for acid-water treatment material in stone production. Safety dust is used in coal mines to prevent explosions. The dust should contain less than 5 percent SiO_2 and 100 percent should pass 20 mesh, with 70 percent passing minus 200 mesh. Finely-ground dolomite and limestone is also marketed by several operations for use as a filler material.

Shale is excavated in Frederick and Rockingham Counties for use as local roadstone and fill material. Sandstone and quartzite is quarried in Carroll, Culpeper, Pittsylvania, Rockbridge and Wythe Counties for the production of roadstone, concrete aggregate, asphalt stone, and manufactured fine aggregate.

Granite, gneiss, diabase, basalt, amphibolite, slate, and marble are quarried in the central portion of Virginia. Major end uses were for roadstone, asphalt stone, and concrete aggregate. Waste slate is crushed near Arvonia in Buckingham County by Solite Corporation. Solite used the slate primarily for lightweight aggregate production. Production of crushed slate, as a by-product of dimension slate operations, increased as a result of local highway construction. Appomattox Lime Company, Inc., mines a marble (Mt. Athos Formation) near Oakville in Appomattox County for agricultural lime.

Fines produced at granite quarries in the southern part of Virginia have been trucked to central Virginia for low-grade fertilizer (D. Via, personal communication). Chemical analyses for granitic materials from Brunswick and Nottoway Counties in the southern Piedmont province indicate K_2O (potash) percentages higher than 10 percent. Potash silicates (orthoclase feldspar) common in igneous and metamorphic rocks release potassium upon weathering.

DIMENSION STONE

Dimension stone product was valued at 2.9 million dollars in 1989. Slate, diabase, quartzite, and soapstone were quarried in the Piedmont Province; slate was the leading stone type quarried, in terms of cubic feet and value. LeSueur-Richmond Slate Corporation mines slate from two quarries in the Arvonia area of Buckingham County (Figure 4). Arvonia slate production dates from the late 1700s when slate was quarried for use as roofing tiles for the State Capitol in Richmond. Slate producers supply the building trade with a variety of products ranging from material for exterior applications, such as roofing tile and flooring, to interior uses such as flooring, hearths and sills. Diabase for use as monument stone is produced by Virginia Granite Company in southern Culpeper County (Figure 5). Quartzite used as flagging material was extracted from two quarries, Carter Stone Company in Campbell County, south of Lynchburg, and Mower Quarries in Fauquier County, north of Warrenton. The New Alberene Stone Company, Inc. is quarrying soapstone from the quarry at Alberene and opened a new quarry site in late 1989. Their products include soapstone fireplaces, woodstoves, cooking ware, and other products of solid soapstone.

FELDSPAR

The Feldspar Corporation operates a mine and plant near Montpelier in Hanover County in east-central Virginia and produces a material marketed as "Virginia aplite," which is

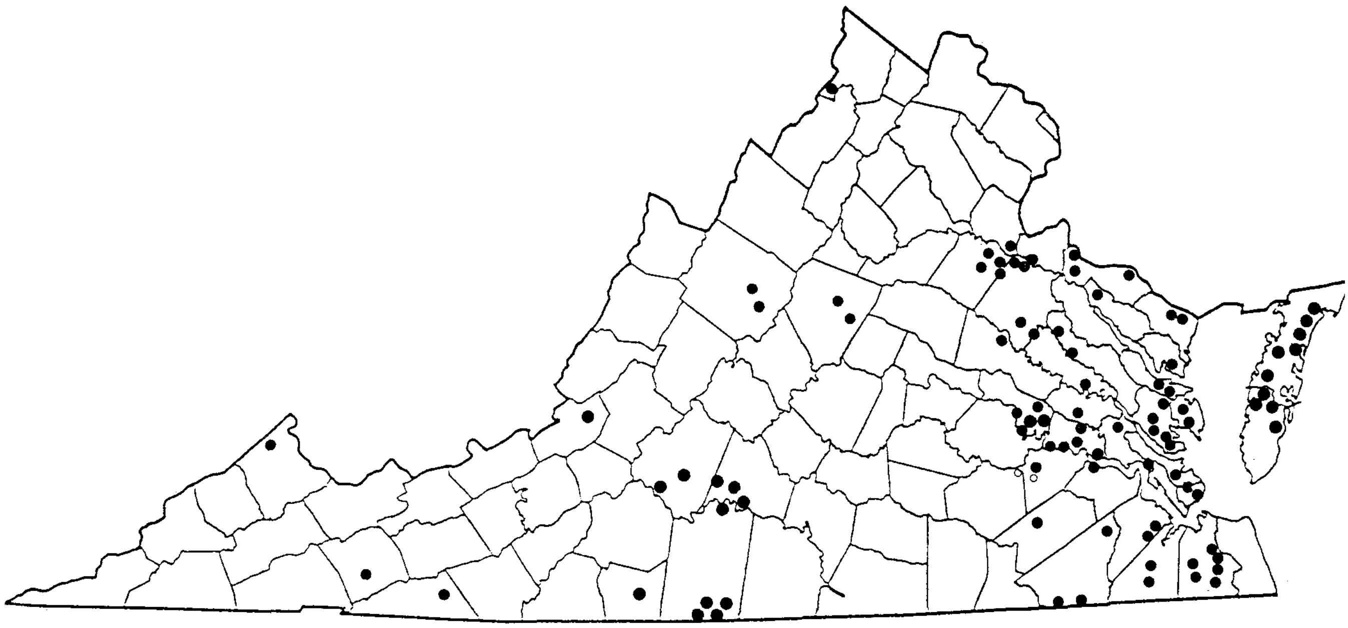


Figure 2. Sand and gravel operations in Virginia.

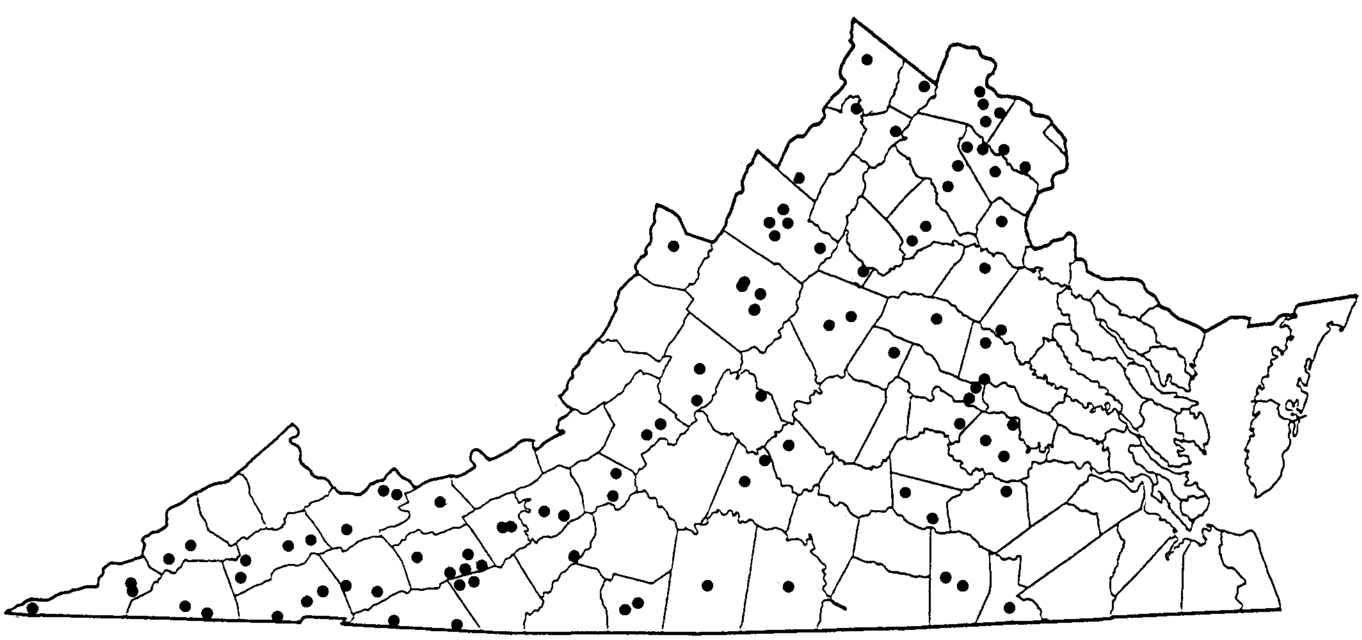


Figure 3. Crushed stone operations in Virginia.

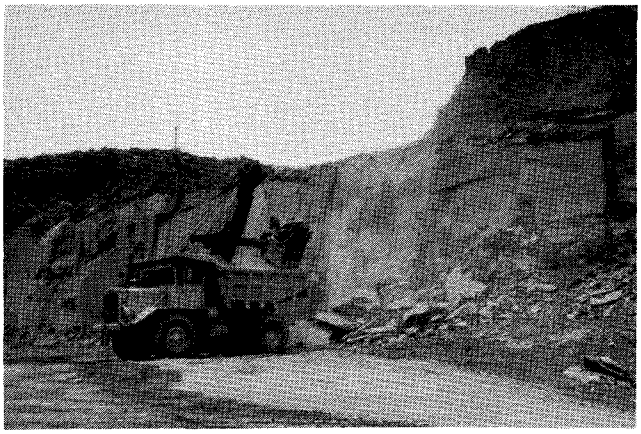


Figure 4. Quarrying of Arvonia slate at LeSueur-Richmond Slate Corporation, Buckingham County.

Figure 5. Drilling diabase at Virginia Granite Company, Culpeper County.

sold to the glass industry. The "aplite" improves the workability of the molten glass and imparts a chemical stability to the finished glassware. Feldspar is mined from medium to coarse-grained meta-anorthosite pegmatites by open pit methods. The rock is trucked to the plant adjacent to the mine for crushing, grinding, classifying and drying. After this processing, the "aplite" is stored in silos. Clay minerals are removed by gravity concentration. Heavy minerals (ilmenite, rutile, sphene) that are present in the feldspar are removed by electrostatic processing and magnets. These minerals were stockpiled until the early 1980's. Processed feldspar is shipped by truck and rail to markets, in New Jersey, Pennsylvania, Ohio, and Indiana.

Clay and silt, with a high percentage of kaolinite and mica, is accumulated in settling ponds. This "tailings" waste material was evaluated in the mid-1960s and was found to be suitable for face brick and drain tile; the material fires dark brown to gray. Fines may have potential as a flux material for the brick industry. About 75,000 to 100,000 tons of this material is added to settling ponds per year.

Feldspar in Amherst County is marketed as aggregate by the W. W. Boxley Company, Blue Ridge Stone Corporation, Piney River Quarry. Fines, resulting from the crushing of feldspar for use as road aggregate, are presently stockpiled. Feldspar has been mined from several pegmatite bodies in the Piedmont province in the past, including those in Amelia and Bedford Counties.

GEM STONES

Mines and collectors in Virginia generated an estimated value of $20,000 of natural gem stones in 1989. The Morefield pegmatite in Amelia County is open to the public for collecting on a fee basis by Powhatan Mining Company; the company also mines and sells "hand picked" mica. Blue-green amazonstone, beryl, topaz, tantalite, tourmaline and zircon are some of the minerals found. Hopkins Enterprises opened a fee basis, collecting operation in Patrick County in southern Virginia. Staurolite crystals (fairystone crosses) are the main interest of collectors at this site.

GYPSUM

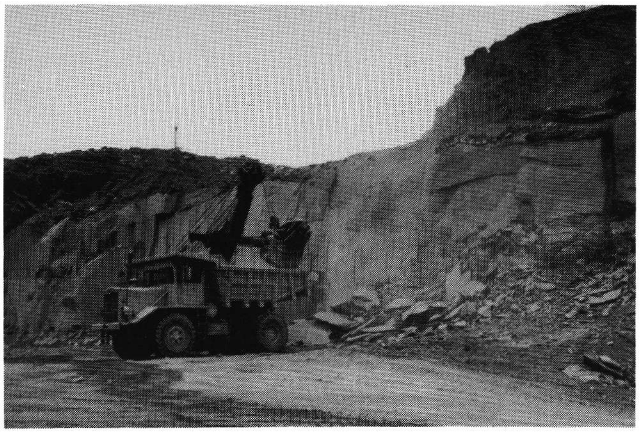
U. S. Gypsum Company operates a mine and plant in the southwestern part of the state. The underground mine is located at Locust Cove, Smyth County. The Locust Cove mine is a slope-entry, multilevel operation. Isolated masses of gypsum in the Maccrady Formation are mined by a modified stoping system. The mined gypsum is trucked to their processing plant located at Plasterco, near Saltville, in adjacent Washington County. The Plasterco plant manufactures wallboard that is used in construction.

INDUSTRIAL SAND

J. C. Jones Sand Company mines industrial sand at Virginia Beach for use in foundry-casting applications as a traction medium. Traction sand is also produced in Dickenson County by Howard L. Daniels Sand Company. Glass sand is produced by Unimin Corporation near Gore in Frederick County from the Ridgeley Sandstone of Devonian age.

IRON-OXIDE PIGMENTS

Virginia is one of four states that produce natural iron-oxide pigments. Hoover Color Corporation in Pulaski County produces ocher, umber, and sienna. The company is the only operation in the United States producing sienna. Raw materials are mined by open pit methods from deposits near the contact of the Erwin Formation with the overlying Shady Dolomite. Deposits, which may be associated with Cambrian age gossans, are concentrated in pockets with insoluble clay and iron oxide. Some iron is also concentrated by precipitation from groundwater. The raw material is trucked to the company plant at Hiwassee where it is pulverized, dried, ground, air separated, blended, and packaged prior to shipping. The finished product, used as a coloring agent in a variety of products, is shipped throughout the United States and to Canada and Mexico. Virginia Earth Pigments Company mines a small quantity of iron oxide from the Brubaker



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#1 mine in southeastern Wythe County. The majority of this material is sold to Hoover Color Corporation.

KYANITE

Kyanite, an aluminum silicate, was first produced in Prince Edward County in the 1920s. Since September, 1986, Virginia is the only state producing kyanite. The majority of the world's kyanite, is produced by Kyanite Mining Corporation from their deposit in Buckingham County. The company produces a concentrate grade of a maximum of 61.8 percent alumina and a minimum iron content of 0.16 percent. Calcined kyanite is converted to mullite at temperatures greater than 3000 degrees Fahrenheit. The mullite is a superduty refractory with a pyrometric cone equivalent of 36 to 37. Products, which are sold in 35, 48, 100, 200, and 325 mesh sizes, are used in the refractory, ceramic, glass, metallurgical, and foundry industries. Mullite aids ceramics and glass melts to resist cracking, warping, slagging, and deforming from high temperatures.

Kyanite Mining Corporation operates two surface mines and processing plants in central Buckingham County, one at Willis Mountain and one at East Ridge. Kyanite-bearing quartzite is quarried from open pits, run through primary crushers, through a log washer to remove clay, and onto the classifiers to remove some kyanite. The material then passes through a rod mill which reduces it to minus 35-mesh size, and then through froth flotation cells so kyanite can be skimmed off. The kyanite is dewatered and then dried; the high temperature of the drier converts the sulfide minerals that are present in the quartzite to oxides. Pyrite is converted to ferrous iron oxide (Fe_3O_4) or magnetite, which is then removed by magnetic separators and stockpiled.

The Willis Mountain Plant processes the raw kyanite which is then trucked to the East Ridge facility for calcining. Mullite is ground and bagged at the Dillwyn Plant and raw kyanite is ground and bagged at Willis Mountain.

Approximately 40 percent of the production is shipped through the port of Hampton Roads to worldwide customers. The company also markets a by-product sand obtained from the processing of kyanite. The sand is sold for golf course, masonry, and concrete sand, and other applications.

LIME

Virginia's lime industry is located in Frederick, Giles, Shenandoah, and Warren Counties. Production from six companies in 1989 was 807,000 short tons valued at more than 33 million dollars (Figure 6). In northwestern Virginia, two companies, W. S. Frey Company, Inc. and Chemstone Corporation quarry and calcine the high-calcium New Market Limestone; and Riverton Corporation in Warren County quarries and calcines limestones from the Edinburg Formation. ShenValley Lime Corporation in Stephens City, Frederick County purchases quicklime and produces a hydrated lime. Two companies in western Giles County (APG Lime Corp. and Virginia Lime Company) operate underground mines in the Five Oaks Limestone. Both companies calcine the Five Oaks Limestone in rotary kilns. Principal sales are to the paper and steel industries.

The paper industry uses lime for regeneration of sodium hydroxide and the neutralization of sulfate water. Lime is used in iron furnaces to remove impurities, and for water purification, and during the last few years, in the neutralization of acid mine water. It is used also for mason's lime, sewage treatment, and agricultural purposes.

VERMICULITE

Virginia is one of three states in which vermiculite, a hydrated magnesium-iron-aluminum silicate, is mined. Virginia Vermiculite, Ltd. operates an open-pit mine and processing facility near Boswells Tavern in Louisa County. Material mined with a backhoe and front-end loader is trucked to the adjacent plant where four inches plus size material is removed, it is washed and run through a rod mill to shear the vermiculite to a thin thickness. Biotite, feldspar, etc. are removed by washing over a riffle table. The vermiculite is further concentrated by flotation cells, dewatered, dried in a rotary kiln and screened to produce four basic size products. Most of the crude vermiculite is shipped by rail in unexfoliated form to North Carolina, West Virginia, Ohio, and other eastern states. Uses for the exfoliated material include packing, insulation, lightweight aggregate, and potting material.

INDUSTRIAL ROCKS AND MINERALS AND PRODUCTS PROCESSED IN VIRGINIA

Many industrial rocks and minerals and products are processed in Virginia with materials imported from out-of-state (Figure 7). These processed products are in part considered in the industrial rocks and minerals (nonfuel mineral production) as calculated by the U. S. Bureau of Mines.

CALCIUM-ALUMINATE CEMENT

LaFarge Calcium Aluminate, Inc. operates a cement manufacturing plant in the City of Chesapeake. Cement clinker is imported and ground into low- and medium-calcium aluminate cement. Six types of calcium aluminate cement are produced at this facility. The advantages of this cement include rapid hardening as well as resistance to wear, high and low temperatures, and corrosion.

GYPSUM

U. S. Gypsum Company operates a processing plant in Norfolk. The Norfolk plant processes crude gypsum from Nova Scotia to produce wallboard and other gypsum-based products. The plant also produces a fertilizer (land plaster) for the peanut industry. The Norfolk facility receives a few shipments of anhydrite from Nova Scotia for sale to cement

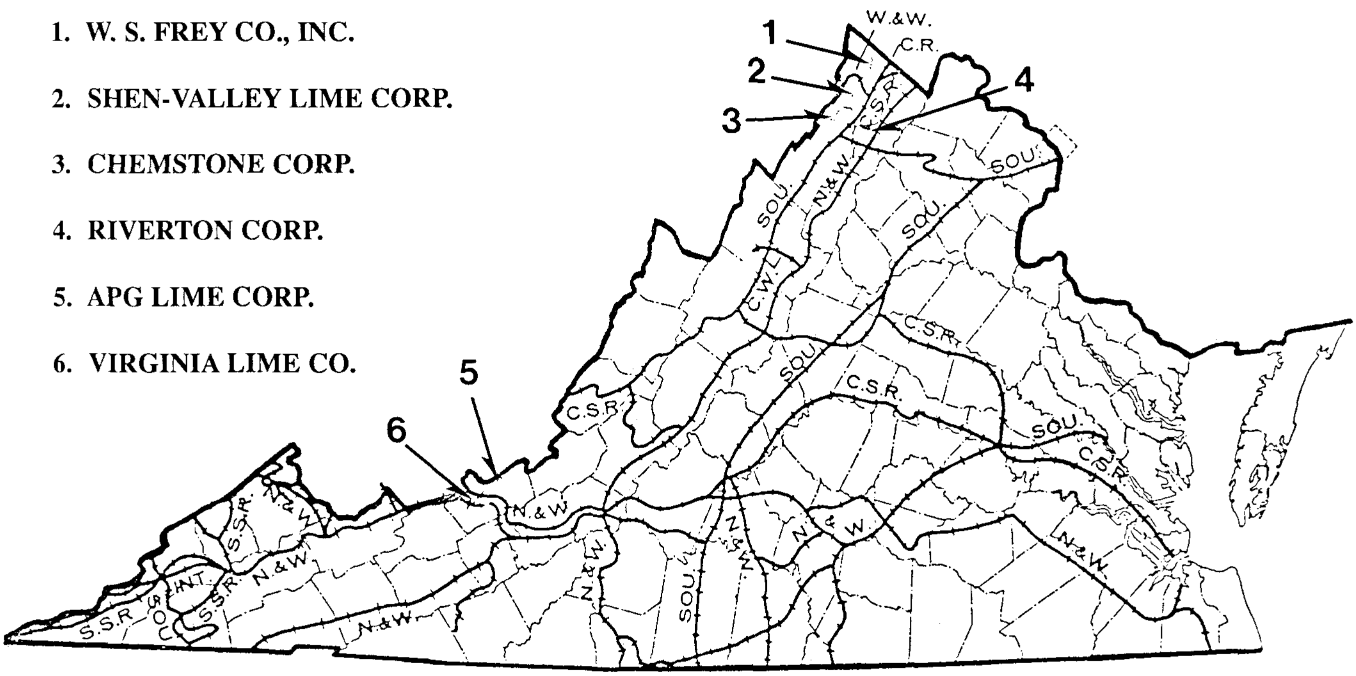

Figure 6. High calcium lime producers in Virginia.

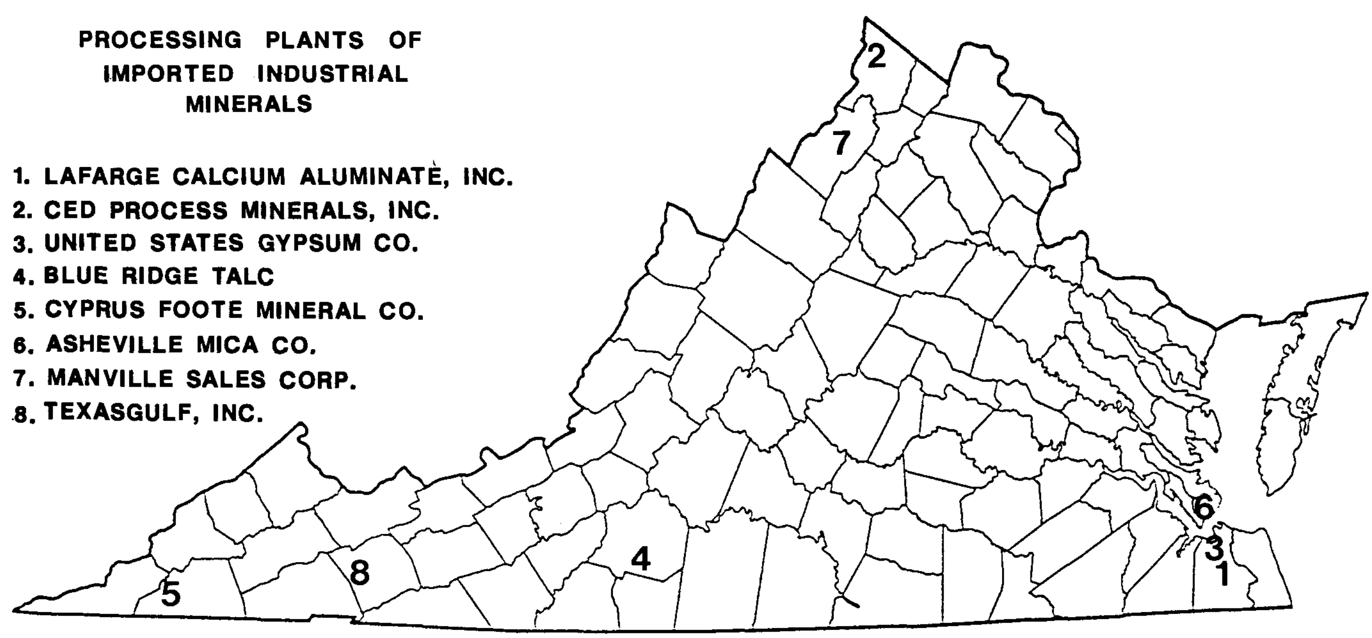

Figure 7. Companies producing industrial mineral materials imported from out-of-state.

manufacturers. The anhydrite is used as a source of sulfur in producing cement clinker.

INDUSTRIAL SAND

CED Process Minerals, Inc., Gore, in Frederick County, recrystallizes purchased sand in a rotary kiln to produce cristobalite, which is marketed as a fine grit (Figure 8).

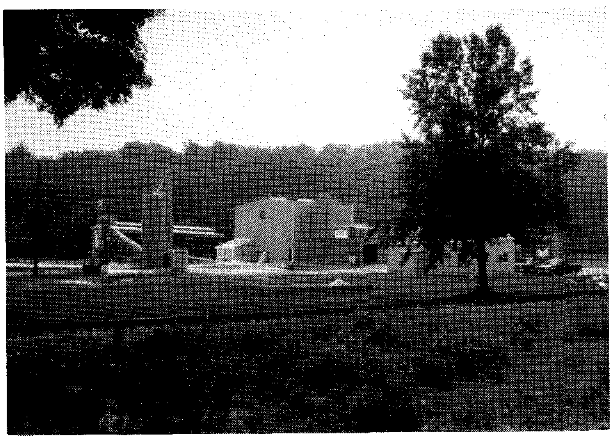

Figure 8. Cristobalite processing plant of CED Process Minerals, Inc. at Gore, Frederick County.

IRON-OXIDE PIGMENTS

Blue Ridge Talc Company, Inc. imports crude iron-oxide pigments from a supplier near the Great Lakes. The pigments are ground and calcined for use in paints and fertilizers, and for cement and mortar coloring. Their markets are both domestic and foreign.

LITHIUM HYDROXIDE

Cyprus Foote Mineral Company purchases lithium carbonate produced from brines in Nevada using calcium hydroxide from various sources to produce lithium hydroxide at their Sunbright plant in Scott County. Lithium hydroxide is used in multipurpose grease applications. In the past, limestone from an underground mine at the Sunbright site was utilized in the manufacturing process and a calcium carbonate precipitate was formed as a waste product. This waste material remains on the site and may have a potential use. The approximate analysis of the material is 43-50 percent $CaCO_3$, 3-6 percent $Ca(OH)_2$, and 40-48 percent water.

MICA

Asheville Mica Company and an affiliate, Mica Company of Canada, process mica at facilities in Newport News. The crude mica is imported from Madagascar and India. Asheville Mica Company produces fabricated plate-mica and the Mica Company of Canada uses splittings from the Asheville operation to produce reconstituted plate-mica. Mica has been produced in the past from pegmatite bodies in several counties in Virginia, including Amelia, Henry, and Powhatan. Mica is presently being "hand picked" in Amelia County.

PERLITE

Manville Sales Corporation operates a plant at Woodstock in Shenandoah County to expand perlite (volcanic glass with high water content and "onion-skin" appearance) obtained from Grants, New Mexico. Expanded perlite is used in the manufacture of roof insulation board which is marketed throughout the eastern United States.

PHOSPHATE

TexasGulf, Inc. ships phosphate rock from its Lee Creek operation in North Carolina to Glade Spring, Washington County. The raw material is then transported by truck to the TexasGulf plant in Saltville, Smyth County. A coal-fired rotary kiln is used to defluorinate the phosphate rock. The product is marketed as a poultry and animal feed supplement in the southern and midwestern states.

SULFUR

Elemental sulfur is recovered from hydrogen sulfide gas by the Claus process during crude-oil refining by Amoco Oil Company. The refinery is adjacent to the York River, near Yorktown. Crude oil is heated in a furnace and fed under pressure into a cylinder where it vaporizes, expands, and condenses into liquid. Hydrogen sulfide is produced and is converted into elemental sulfur. About 50 tons of sulfur is produced per day and is marketed to a buyer for use in fertilizer.

manufacturers. The anhydrite is used as a source of sulfur in producing cement clinker.

INDUSTRIAL SAND

CED Process Minerals, Inc., Gore, in Frederick County, recrystallizes purchased sand in a rotary kiln to produce cristobalite, which is marketed as a fine grit (Figure 8).

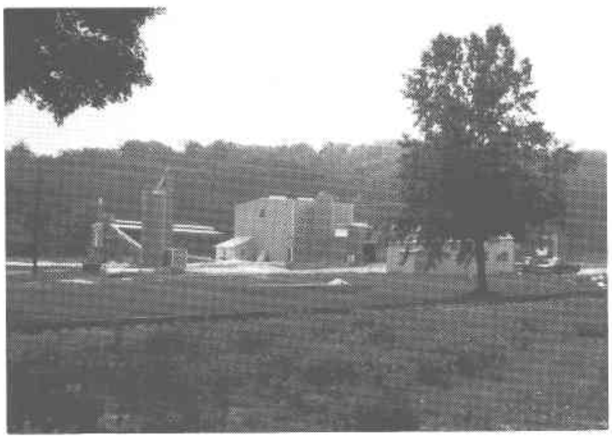

Figure 8. Cristobalite processing plant of CED Process Minerals, Inc. at Gore, Frederick County.

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NON-FUEL MINERAL INDUSTRY AND PRODUCTS IN SOUTHWEST VIRGINIA

James A. Lovett
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ABSTRACT

Southwest Virginia is most commonly known for abundant coal and natural gas resources. However, the region has many non-fuel mineral resources and supports a relatively strong and stable construction materials and industrial minerals industry.

West of 81 degrees longitude, limestone and dolostone are produced at twenty quarries from formations of Cambrian, Ordovician, Silurian, and Mississippian age. Sand is produced from two quarries in Cambrian-age sandstone and from two alluvial deposits. Shale and residual clays from Cambrian and Ordovician formations are worked at four sites. Gypsum is mined from Mississippian-age rocks, and granite gneiss is quarried from Precambrian gneiss.

These operations produce a wide variety of mineral products. Limestone and dolostone quarries produce a range of aggregate for road construction, railroad ballast, septic-tank drainfield rock, riprap, mine safety dust, glass manufacture, industrial fillers, agricultural and soil treatment products, roofing materials, and structural and architectural block. Sandstone, sand, and river gravel are used as aggregate in concrete, asphalt, and brick mortar. Shale and clay are used to produce brick products and clay dummies. Gypsum is processed to produce a variety of wallboard products. Granite gneiss is quarried to produce non-polishing aggregate. Lithium, magnetite, and phosphate from out-of-state sources are processed into chemical and agricultural products.

INTRODUCTION

The minerals industry of Virginia has been dominated by coal production throughout the 20th century. In 1988, the total value of mineral production in Virginia was almost 1.8 billion dollars (Table 1). Production of non-fuel mineral resources was valued at about 495 million dollars in 1988, or approximately 28 percent of the total. Coal, mined exclusively from the southwest Virginia coalfield located west of 81 degrees longitude (Virginia Department of Mines, Minerals, and Energy, 1989a) (Figure 1), was valued at more than 1.2 billion dollars in 1988, or almost 70 percent of the total. Natural gas, which is also produced exclusively from wells in southwest Virginia, west of 81 degrees longitude (Virginia Department of Mines, Minerals, and Energy, 1989b) (Figure 1), was valued at almost 42 million dollars, or a little more than 2 percent of the total. Collectively, coal and natural gas produced in southwest Virginia accounted for about 72 percent of the total value of mineral production in 1988 (Table 1).

Although southwest Virginia is most commonly known for abundant coal and natural gas resources, the region also has a wide variety of non-fuel mineral resources and supports a relatively strong and stable non-fuel mineral industry. The region utilizes abundant carbonate and quartzite resources to supply construction materials to local markets, and takes advantage of unique geologic resources and manufacturing technology to supply specialty products used locally and shipped throughout the eastern and southern states.

NON-FUEL MINERAL PRODUCERS

Twenty quarries produce limestone or dolostone in southwest Virginia, west of 81 degrees longitude (Figure 1), from the abundant carbonate resources found in the Valley and Ridge physiographic province. Production is from several geologic formations including the Honaker Formation, Maryville-Rutledge Limestones, and Conococheague Formation of Cambrian age; Stonehenge Limestone, Mosheim Limestone, Lenoir Limestone, Effna Limestone, Rockdell Limestone, Benbolt Limestone, Hurricane Bridge Limestone, Woodway Limestone, and undivided limestone beds of Ordovician age; Hancock Limestone of Silurian age; and Greenbrier Limestone of Mississippian age. Most quarry operations throughout the region produce a wide variety of crushed stone for road building and general construction. The most common uses of the limestone and dolostone aggregate include roadbase material for public and private coal mine roads, and graded aggregate used in asphalt and concrete. Other uses include railroad ballast, septic-tank drainfield rock, and rip-rap for reclamation of mined land and erosion control.

In addition to construction aggregate, specialty limestone and dolostone products are produced throughout the region. Dolostone and dolomitic limestone are produced in Russell County for use in soil treatment products, fertilizer fillers, animal feed supplements, roofing materials, structural concrete products, and architectural block. Chemical grade dolostone is produced in Russell County for use in industrial fillers and glass manufacture. Quarries in Russell and Tazewell Counties produce mine safety dust, which is pulverized limestone or dolostone (at least 70 percent passing through the 200-mesh sieve) with low silica content (less than 4 percent free and combined silica) used in underground coal mines to help prevent explosions from airborne coal dust. Gypsum supplied from outside of the region and locally quarried dolomitic limestone are finely ground and pelletized in Russell County to provide agricultural, lawn and garden soil treatment products that dissolve quickly and are virtually dust free. Agricultural limestone ("ag-lime") is produced in Bland, Lee, Russell, Tazewell, Washington, and Wise Counties.

Three shale pits, one clay pit, and two processing plants

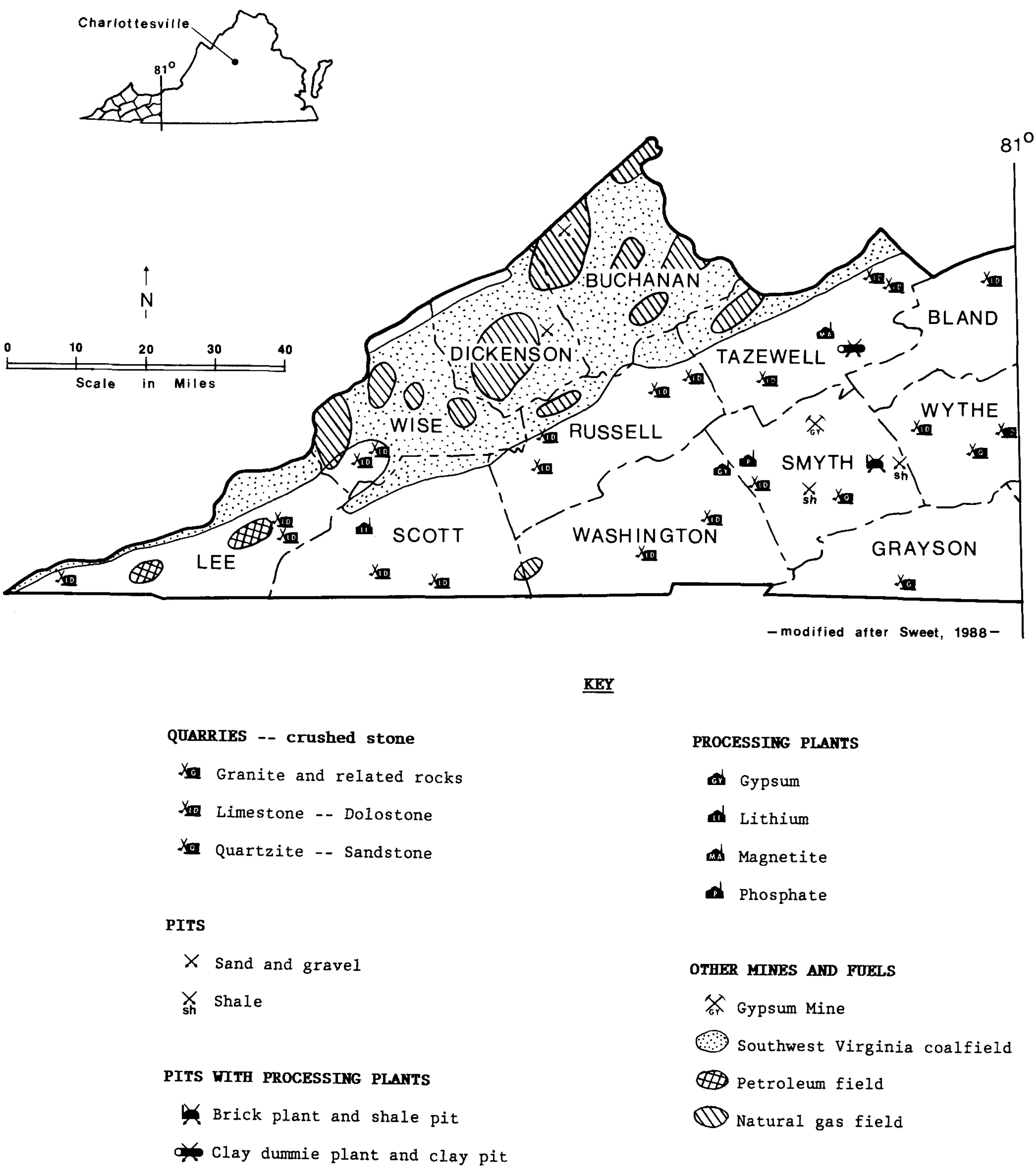

Figure 1. Mineral industry in southwest Virginia.

Table 1. Mineral production in Virginia, 1988

Mineral Material	Quantity	Value (thousands)	Percent of total mineral production
Coal (bituminous)[1] (\$26.49/ton)[2]——(thousand short tons)—	46,365	\$1,228,209	69.6%
Natural Gas[3] (\$2.23/1000 cu.ft.)——(million cubic feet)--—	18,683	41,663	2.4%
Nonfuel minerals[4] (total production)—	XXX	494,512	28.0%
Petroleum[3](crude) (\$13.95/bl)————(42-gallon barrels)—	24,952	348	<0.1%
TOTAL —	XXX	\$1,764,732	100.0%

XXX Not applicable.
[1] Virginia Department of Mines, Minerals, and Energy, 1989a.
[2] Energy Information Administration, 1988, p. 114.
[3] Virginia Department of Mines, Minerals, and Energy, 1989b.
[4] Prosser and Sweet, 1988, p. 2.

are located in southwest Virginia, west of 81 degrees longitude (Figure 1). Shale is worked in Smyth County at two large pits in the Rome Formation of Cambrian age and one small pit in the Rich Valley Formation of Ordovician age. These operations supply shale to a brick manufacturing plant in Smyth County that is capable of producing as many as two million bricks per week. A small company in Tazewell County removes residual clay from shale in the Martinsburg Formation of Ordovician age and manufactures extruded clay dummies used to pack blasting holes in coal mines.

Quartz sand is produced from two quarries and two river-bed alluvial deposits in the region (Figure 1). Quartzite is quarried in Smyth and Wythe Counties from the Erwin Formation of Cambrian age, a prominent ridge-forming unit in the southern part of the Valley and Ridge province. The quartzite is generally weathered and very friable at the quarry sites, and does not require blasting. At both quarries, the quartzite is processed to disaggregate the fine-grained to granular sand for use as fine aggregate in asphalt, concrete, and masonry cement. A small amount of sand and gravel is also produced in the region from two river-bed alluvial deposits. Washed and screened sand is recovered from the Russell Fork in Dickenson County and the Levisa Fork in Buchanan County, and used locally as fine aggregate in masonry cement and asphalt.

Gypsum is mined in Smyth County and processed into wallboard in Washington County (Figure 1). The gypsum ore occurs primarily in grayish-green to grayish-red mudstone and shale deposits in the Maccrady Formation of Mississippian age (Sharpe, 1985). As a result of postdepositional deformation, the gypsum deposits occur as stacked and discontinuous lenticular bodies. The gypsum ore is milled and calcined at the mine site in Smyth County, and then trucked to the wallboard manufacturing plant in Washington County. This plant produces 83 kinds of wallboard for residential and commercial applications, and has the capacity to produce enough wallboard to make 80 three-bedroom homes per day.

Granite gneiss is quarried west of 81 degrees longitude at one location in Grayson County (Figure 1). The quarry is in the Cranberry Gneiss of the Elk Park plutonic group of lower Precambrian age, which ranges in composition from diorite to granite. Crushed stone from this quarry qualifies as non-polishing aggregate, and is produced primarily for use as roadbase material, graded aggregate in asphalt base and surface course mixes, and concrete.

Three plants process mineral compounds from out-of-state sources into chemical and agricultural products (Figure 1). Lithium carbonate is processed in Scott County into lithium hydroxide which is used to manufacture other lithium based products such as lithium grease, lithium salts, storage batteries, and compounds to absorb carbon dioxide. Phosphate rock is processed in Smyth County to produce defluorinated phosphate which is used as an ingredient in animal feed supplements. Magnetite is processed in Tazewell County for use by coal preparation plants that employ heavy media washing systems. These preparation plants use magnetite to control the specific gravity of the fluid bath and recover fine coal particles.

Additional information on these selected operations and all active non-fuel mineral production operations throughout the state is available in a directory from the Virginia Division of Mineral Resources (Sweet and Wilkes, 1990). This directory is updated and published about every two years, and includes company names, address, telephone number, mineral commodities produced, geologic data on the source rock worked, and location map for more than 300 operations.

SUMMARY

Southwest Virginia west of 81 degrees longitude supports a relatively strong and stable non-fuels minerals industry that produces construction aggregate, industrial minerals, agricultural products, and specialty mineral products. Most construction aggregate, which includes crushed limestone, dolostone and quartzite, is used in local markets. Some products, such as gypsum wallboard, dolostone and limestone agricultural products, chemical grade dolostone, and face brick, take advantage of geologic resources that are unique to the region and are marketed throughout the eastern and southeastern states. Other products, such as mine safety dust, rip-rap used in reclamation of mined land, structural concrete products, manufactured clay dummies, and processed magnetite, are also unique to the region and produced to supply markets directly created by the coal mining industry.

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REZONING AND PERMITTING QUARRY SITES

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Vulcan Materials Company was granted a rezoning classification and special use permit for a new quarry in Stafford County, Virginia on December 19, 1989. The vote of approval came after several minutes of discussion during the meeting; however, the road to this point involved hundreds of manhours of work and careful planning. The amount of work done towards each individual zoning or site permitting plays an important role in each case, but more importantly, the company's history of operational responsibility plays a major part in this process. In today's climate of controlling urbanization and growth, the day of the irresponsible and unconcerned mine operator are gone. The operator who thinks that he can ignore blasting, dust or truck problems will soon be paying a visit to the unemployment line, much less getting new operations opened.

Only when a company is confident about its operational responsibility, public image and its efforts to become an "About Face" company, should it attempt a rezoning-permitting situation. The average zoning or permitting procedure often costs hundreds of thousands of dollars; therefore, the company's operating history and environmental stewardship commitment and concern has to be in order or the amount of money invested in a rezoning situation will be of no consequence.

The area to be chosen for an expansion (greenfield site) should be in an area of present or future market potential. This market phenomenon is what makes the location of permitting so difficult. In order to have a thriving, bustling market, a location must have active housing, road building and a growing economy in order to create the need for a generally low-cost product with a high transportation cost. This necessitates that the quarry site be close to growth areas; however, the growth areas are the most controversial places for a quarry. Producers could get an operation zoned fifty miles from town; the only problem is that the product may not sell if you can't be the low cost supplier to the market.

Once a potential market is located, the real work begins. A high quality deposit must be located and ample reserves proven for future growth. The mineralogy of the deposit must be evaluated completely and concerns about environmental matters must be anticipated from neighbors and citizens. A deposit needs to be located with sufficient buffer land, agreeable landowners, good transportation access and in a fairly remote area that protects neighbors environmentally. Lack of any of the above could spell defeat for a permitting proposal.

The next step is to acquire or lease the land involved. Once this is done, a zoning attorney needs to be brought on line along with necessary consultants to present specific areas of expertise. Often mining companies attempt to do this "In House;" however, their credibility is diminished in that they are perceived as the "biased applicant." Independent firms which generally are known as the tops in their field should present the facts and information in report form to the permitting body. Much of this information must be site specific to the new operation. Every application will involve the same controversial factors which include: Hydrology, Property Values, Blasting, Transportation, Trucking, Geology, Dust, Environmental, Archaeological and Engineering. You must anticipate that all of these subjects will be brought up. The applicant should be prepared with facts to demonstrate that these factors are not adverse to the area.

Homework completed, the applicant will most likely face emotionally concerned adjoining neighbors at a public hearing. Many of these people will be loaded with misconceptions and fears about the mining industry. These fears should be addressed at the beginning of the meeting. This meeting is also where "skeletons in the closet" of an operations past can kill the application. A producer, applying for a permit, who has consistently ignored neighbors and good operating practices, will be shouted out of the room upon stating that he will comply with all regulations for his proposed sites. What is this producer to do? He cannot go back and change what has gone on in the past. The answer, therefore, is that he must begin a responsible mode of operation today and return with a proposal in five to ten years. On the other hand, the responsible producer will have adjoining neighbors of existing operations testify to the permitting body, favorable experiences with the operator. The industry cannot place a value on favorable statements that are the result of well managed, concerned operators. Once the permitting body hears these comments from neighbors to existing operations, the political decision that they will make on a proposed similar operation in their district will be more favorable.

In conclusion, an existing expansion (greenfield site) proposal must be in the right place - at the right time, with the right conditions, and have sister operations which have consistently operated in a responsible manner in the past; after all, is it not often said "One's future is judged by his past."

EVERY LAW CREATES AN OUTLAW*

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ABSTRACT

Adversarial relationships, between the Regulator and the Regulated, are expanding daily and resulting in prejudicial decisions instead of practical ones. One upmanship has gone beyond romance, politics, sports and the stage into an area where reason should be paramount, and is necessary for the continuation of our way of life.

This paper will discuss the rhetoric, response/retaliation and lack of reasoning affecting the industrial minerals mining industry. To the degree possible, it will be a bipartisan presentation reflective of the author's experience in both arenas. Suggested modus operandi will be offered to promote cooperation in lieu of confrontation and therefore, with consequent benefits to everyone.

The purpose of this presentation is not to critique existing mining laws but rather to appeal for a fair and cooperative enforcement of those laws. Early mining laws and for the most part, Federal, beginning with the Mining Law of 1872, were primarily concerned with land or mineral lease acquisition and maintenance of possession. Today, clear title does not necessarily guarantee the right of development due to the advent of hundreds of thousands of laws by various entities.

Frustration and contradiction stemming from minerals regulatory authorities is not Johnny-come-lately. (Please be aware of the distinction between the "regulations" and the "regulators".) Profits were allowable to Roman individuals for the use of a property under the Justinian Code of the Sixth Century. Under this usufruct system, state mines were operated as long as no damage was done to the property but the opening of new mines on the property was a violation of the usufruct. Pliny the Elder indicated in his writings that the Italians considered mining as a land abuse to be discouraged in the Motherland but permissible in conquered lands. These are ancient laws but with modern day rings of familiarity to most of us.

To set, to the degree possible, the bipartisan tone of this presentation, be reminded that the previous paragraph is taken almost verbatim from a planned presentation entitled, "Both Sides of the Coin." Byron Cooper (1966) further set the stage at the First Midwest Forum in this bipartisan discussion:

"...Some of the government experts took positions that were on occasion ludicrous and indefensible. Geologist "X" deprecated the opinions of all experts who did not agree with him, and also rejected many authoritative publications of the government by saying all were "untrustworthy," whereupon he interposed his own definitions and added "I am more definite about it than most people who work with the field."

"In the Erie Stone Company case, Geologist "Y" identified as "sloppy" those definitions of limestone that did not agree with his own, and said he felt very poorly toward some geologists because of their sloppy definitions. Geologist "Z" appeared as a government witness in the James River Hydrate Company's case and argued that dolomites were not classed with limestone by most geologists. I think these gentlemen missed the main point that was before the courts; their individual opinions were irrelevant." The quoting of Mr. Cooper here is to emphasize that regulators do not hold the patent on ludicrousness.

We have all broken laws! If there is one person here who has not, I will end this presentation now. Okay, we have now established the common thread of criminality, henceforth we will discuss degrees of guilt. Now that the sanctimonious have been brought to their knees, I would like to lay a guilt trip on everyone, and particularly on the regulators brave enough to be in the audience. Please remember that you, all of you, are consuming, and I will be so bold as to state an equal amount, of mined products as the rest of us. Therefore, I would like for you to consider yourself a part of any problems allegedly caused by mining rather than an extra-terrestrial being without extractive mineral industry sins.

My aim here today could perhaps best be accomplished by asking that all attendees and others who may review the Proceedings, would reread the many presentations with a similar purpose given at a number of previous forums. Many of those specific presentations are quoted and/or listed as references for this paper. I have excerpted freely, with proper credit and sincere appreciation.

A sampling follows: Ian Campbell (1967) said at the Third Forum, "The future of the industrial minerals is indeed bright and the touchstones for assuring and further brightening that future lie in research, (research in exploration, mining, beneficiation, transportation and applications), in innovative thinking and planning, and — most important of all— in social and political cooperation."

Lance Meade (1969) asked the rhetorical question at the Fifth Forum, "How can an industry which has been the

* "Title borrowed from and used with the full permission of Maxine Stewart, Hazen Research, Golden Colorado - from a newsletter article written by Ms. Stewart."

supplier of the raw materials that have enabled our present day technically advanced society to develop, allow itself to be faced with possible extinction by this same society?"

To aid in your search for humility, I hope, read Larry Rooney's (1970) Keynote Address from the Proceedings of the Sixth Forum - held in Michigan.

To show that the aggregates industry is and has been aware of problems/solutions, critique William E. Hole, Jr.'s presentation, "Environmental Problems and the Construction Aggregates Industry," also presented at the Sixth Forum.

Peter T. Flawn (1972) said: "It seems clear that without an enlightened national mineral policy that defines the interests and objectives of the nation and sets out specific actions required to accomplish those objectives, United States' industry will face potentially destructive supply problems in obtaining raw materials, including mineral fuels, and potentially destructive economic problems in maintaining operations. Indeed, the economic impact will extend far beyond the mineral industry. The solution to the anticipated problems lies in the public policy area."

Jim Dunn (1982) asked the question: "How can we solve the basic riddle of resource management in the broad public interest? The changes needed are educational, mental and legal." I would add, and without a thought of correction of Mr. Dunn, an education for the legal profession.

I perceive as a basic problem in the "law/outlaw" dilemma, that we have too many lawyers acting as pseudo geologists, hydrologists, engineers and certainly, as politicians. Perhaps the reverse is true as well for I find that increasingly I'm asked an opinion as to what some rule or regulation means or how some agency is likely to respond. The epitome of this dilemma is the familiar, "What was the intent?"

We, as geologists, must bear our fair share of the responsibility for this dilemma. For too long, and would that it could continue, we have been content, maybe even pompously so, to be closet scientists and leave the politicking to someone else. The plethora of laws written to thwart or benefit developers but which affect, and normally adversely so, the mining industry, are well known to most of you. Similarly, there are blanket laws written, and often passed, regarding "Mining operations will, must... etc.," when they should read so as to apply to a certain commodity at worst, and in a certain geologic province. As distasteful as it may be, you/I need to be sure that legislators/regulators know whereof they speak.

To the contrary, some laws have favored mining as indicated by Wally Fields (1971) at the Seventh Forum, "...from the beginning of time until 1967, the only Florida laws directly governing mining operations were the three simple little laws..."

"In 1891, Sec. 768.10 F.S. was adopted. This law made it unlawful for any person to leave a pit or hole open which had a depth or breadth of more than two feet, unless the same was enclosed by a fence to prevent horses, cattle or other domestic animals from falling into the same. The act goes on to say, however, that the law shall not apply to persons engaged in mining operations so long as those operations continue."

The following statement has been used on several occasions and to those of you who may have heard it, I apologize for repeating it. However, Professor R.A.L. Black's statement, "Society should be reminded that nearly all the amenities of modern life which it takes for granted are products of the minerals industry and the engineers and others who serve it" is as true today as almost 12 years ago when I first quoted him (Timmons, 1978). W. L. Dare, a Wilderness and River Basin Coordinator for the U.S. Bureau of Mines recognized this paradox in saying, "...while affluence has motivated our support to preserve the quality of the natural environment, industrial development is needed to support the affluence."

To you here who may be regulators, now the fourth branch of government, with EPA a cabinet level agency, I recommend as required reading, "Industrial Minerals, Can We Live Without Them?", by Hal McVey from the April, 1989 issue of Industrial Minerals. To the pure and puritan geologists in attendance, I suggest reading and practicing the comments by Karl W. Mote in the March, 1990 issue of Geotimes.

My contention of several years ago that the Regulatory Branch was now the fourth branch of government is supported by this Rock Products statement:

"As early as 1952, Supreme Court Justice Robert H. Jackson warned: 'The rise of administrative bodies probably has been the most significant legal trend of the last century and perhaps more values today are affected by their decisions than by those of all the courts. They have become a veritable fourth branch of the government, which has deranged our three-branch legal theories as much as the concept of a fourth dimension unsettles our three dimensional thinking (Timmons, 1978).'"

Most adversarial relationships are fostered by egotistical maniacs, pompous donkeys, or in the case of the extractive industry, overzealous regulators or stubborn industry personnel. Quite often, the players are similar to reformed smokers, former drug abusers or alcoholics and please, I mean no disrespect whatsoever. The point is their reformed halos restrict their ability for clear, objective reasoning. Remember, a halo has but to slip a little to become a noose. However, an appreciation borne of experience on both sides of the coin, may be the only fair and effective way legislation/regulation can be designed. To reiterate, realize you are also part of the problem, even more so than a part of the solution.

The NIMBY syndrome has become so commonplace that the acronym itself needs no explanation. The extent to which this syndrome is active is virtually all inclusive. We, and notice the inclusive pronoun, under the NIMBY syndrome, object to rock quarries, rock concerts, rock haul trucks, rock dust...everything with a rock description except when it applies to a diamond. We also object to shopping centers, landfills, airports, highways, office buildings, manufacturers, chemical plants, light noise, vibration, dirty air, dirty water, dirty language, insurance costs, high medical bills, gas prices, ad infinitum. Name me one of those objections to which any of you can say you do not contribute.

A NIMBY story and in my backyard - The City of Jacksonville - needs a new landfill site desperately. If you consider our geographic position, and would hazard (no pun intended) an educated guess at the geology, you realize the inherent problems; a high water table with a highly permeable and comparatively thin sand covering, overlying the Floridian Aquifer, the source of most of our water supply. From all indications, the solution to this site search has been to begin with the legal aspects and add in, maybe, the geology as an afterthought. Part of the legal evaluation has been to have the "City's lawyer walk over the property at $175.00/hour." (This fee was recently raised to $190.00/hour, but public disclosure and subsequent outcry caused it to become "a mistake.") To this country boy, approach the problem in the same order as occurrence; geology first and the lawyers subsequently, after physical suitability has been determined.

The proposed Jacksonville landfill is complicated by the fact that the proposed site is located adjacent to the St. Johns County line, in the extreme southeastern corner of Duval County-Jacksonville. Need I further tell you that St. Augustine, reputedly the oldest permanent settlement in North America, is in St. Johns County. Jacksonville's Mayor, presumably, according to the local newspaper, filed a suit to compel the existing landfill site in St. Johns County (serving St. Augustine) to conform to the same regulations as the proposed site to serve Jacksonville. Adversarial relationships? You be the judge!

At a city council meeting in Tallahassee a few years ago, a council member proposed that all borrow areas, mined pits, etc., be filled back to original grade. This seemed like a good idea until the State Geologist, who luckily was in attendance, pointed out that in order to do that, other holes would have to be dug. Sounds like a good military exercise, eh? Be careful lest your laws create outlaws or more problems than they solve.

On March 12 of this year, a quarry operator in the Northeast (no state names by choice, not by request) told me of a runoff water controversy at one of his operations. A series of settling ponds were utilized to clarify process water for recycling, with releases from the clarified pond only during periods of heavy rainfall and plant inactivity. To insure that no turbid water would leave the site, he designed a collection system for casual water also to flow into his settling ponds to fully clarify that water. DEP said "no", because that now becomes process water. So, he is now destroying the casual water collecting system and allowing it to flow directly into the natural system, turbidity notwithstanding. Practical, prejudicial, by the book, whatever...another outlaw created, government mandated and supported.

Unfortunately, another paradox exists which strikes at the very roots of what this country has stood for throughout the centuries. A little story about Francesca Monjiardo of Whitesburg, Kentucky as an illustration: Francesca came to this country from San Andrea through Ellis Island in 1902 and became part of the sizable Italian community in Whitesburg (Caudill, 1980). Because of pronunciation difficulties and other reasons, he became Americanized as Frank Majority and the name became commonplace to him. The conditions of immigration for many in the Italian community were quite similar to the Mariel Boatlift, but Frank Majority strove, almost too hard, to be an exemplary citizen. As such, during WWII, he dug coal for himself and a couple of his neighbors from a thin seam which outcropped next to his house. Tools of recovery were a mattock and shovel, pick and wheelbarrow. The S.F.A., Solid Fuels Administration, having decreed that nearly all coal should be used in the war effort, notified everyone by post office poster that any "person, firm or corporation engaged directly or indirectly in the production of coal"...must register with the S.F.A., receive a code number, have his output allocated and price fixed. Failure to do so could mean a "$10,000.00 fine, ten years imprisonment or both." Frank Majority was inundated with mail; wanting to know what vein he was mining and its prox analysis, number of employees, amount of electricity he was consuming, number of rubber-tired vehicles (I don't know if the wheelbarrow qualified) and diesel or gas powered, wages per hour, day and week, tons produced daily, names and addresses of all customers and price charged per ton, probable production for each month of the coming year and that he could charge $3.85 per ton and must ship to the "designated war industry." Frank abandoned the little coal pit and the stove ran short, but the torrent of mail continued. One day Frank gave up and quit. He said, "I just serva the time, but I no answer the questions. Ten years onna rock pile is better thanna ten years answer the questions!" The entrepreneur, the small businessman, the backbone of this country, forced (literally) out of business. I wonder if Frank became one of those faceless figures in the commodity lines of Eastern Kentucky? Consider the total consequences of your actions!

Two ridiculous stories, from opposite sides of the coin, and these are but two of thousands, no doubt. R. Lee Aston in the December, 1989 issue of Pit & Quarry, states:

"In an unusual case, Town of North Hampton vs. Sanderson, a sand and gravel producer in New Hampshire tried to operate without permits by spoofing the courts into believing he was actually a home builder.

Although the producer operated a 14-acre gravel pit in a residential subdivision for more than eight years, he claimed his main purpose was to prepare building sites.

The producer said he was merely trying to lower the elevation of the lots to that of the road. Since he was not 'officially' a mining operation, he claimed he was not required to obtain mining permits from the state or use permits from the town zoning board."

Having had very recent experience in the area, I can vouch for numerous similar permits issued to prepare residential lots. Equally questionable are the permits issued for "digging a lake" in Dade County, Florida. Childish, yes, but I have often stated that if you persist in childish treatment, you will eventually evoke/provoke childish responses.

And now the other side - a Citizens Advisory Group to the St. Johns Water Management District in Florida recently experienced a unique attempt at regulatory enforcement. Brooklyn Lake, north of Keystone Heights, has been drying up as have many sinkhole type lakes in Florida, due to the continuing drought (Guerry McClellen, 1990, personal communications). Their (the Advisory Group) concern and subsequent efforts resulted in obtaining a work force from the Lawtey Correctional Institute to clean out an inflow ditch in hopes of raising the water level. A member of the St. Johns Water Management District Board told the group no permit would be needed for such activities. While performing the "clean-out" chores, the convicts were leveling or smoothing the bottom and sides of the ditch. A cruising DER member questioned the activity without a permit and threatened to arrest everyone. This overzealous regulator was informed of what a neat trick this would be inasmuch as all currently were assigned numbers, cells, etc. Newspapers had a field day.

Solutions, I can only suggest.

To the regulators, be as informed as possible to the total consequences of your efforts and as educated as possible about the entity you are entrusted to regulate. Your subjective tasks must be approached with as much objectivity as you can muster. Be reminded that complete objectivity is possible only with machines...and they are being influenced by the programmer.

The miners/geologists must be active in the political/public policy arena. Become involved before the crisis stage and before adversarial relationships begin to form. Our world is too confined for our activities as either law-makers or law-breakers, as maybe I have suggested, not to affect fellow human beings. So, approach your tasks with a purpose of cooperation, not confrontation.

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COMPUTER APPLICATION FOR RESERVES ANALYSIS AND MINE PLANNING

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ABSTRACT

The process of determining the finished land form of a sand and gravel operation, before mining begins, involves the systematic integration of a variety of data. This information consists of local land use policies, environmental regulations, reclamation standards, mining procedures, earth moving equipment, site conditions and most important of all, deposit characteristics. The quantity, quality and distribution of both the overburden and the deposit are crucial for pre-mine planning. Equally important is the need to predict the ultimate configuration of the mined-out deposit relative to adjacent land elevation, ground water table and contour of the deposit floor. This paper presents a case study of a sand and gravel pre-mine reclamation project. It illustrates the interaction between the geologist and landscape architect and the pre-mine planning process.

Our client had data from 75 test borings that had been drilled to evaluate a sand and gravel deposit. Surfer, a computer program, required an x, y and z coordinate for each test boring. In addition, the program used drill logs and test data to supply information about the overburden thickness, the depth to water, the thickness of the minable sand and gravel and the amount of the deposit that lies above and below water. Output from the program consisted of the following maps: a topographic map, a property map with a grid to show test boring locations and isopach maps of overburden, deposit thickness, and thickness above and below water. These graphics illustrated the characteristics of the deposit as the key data for the mining and reclamation plans.

These data were then analyzed to resolve three questions. First, what areas of the deposit have the best reserves and the highest potential for land development? Second, how can the overburden be used most efficiently to create usable land? And third, what extraction pattern would be most beneficial to both the mining and the land development operations?

INTRODUCTION

The project began with a meeting between the client, the landscape architect and the geologist. The client owns nearly 800 acres from which they expect to mine sand and gravel. In the interest of making maximum use of the land and resources, the client wanted to develop a mining and reclamation plan at the beginning of the program. Not only would the plan be the basis for their operation, but it would also serve as the foundation for acquiring the necessary mining permits.

The landscape architect outlined the geologic information that would be needed to initiate their work. They needed to know the boundaries of the deposit, the thickness of overburden, the depth to water, and the amount of deposit above and below water. These characteristics of the deposit were necessary for the development of a long range mining and reclamation plan.

A review of the existing drill data showed that parts of the property had not been drilled and that additional drilling and testing was necessary to complete the required information. Previous drilling consisted of 60 test borings, but samples were collected and tested from only 17 of those. We decided to drill 16 additional holes to better define the boundaries of the deposit and to collect samples for analysis to confirm information about the 43 holes where no samples had been taken.

The landscape architect and geologist discussed how best to present this information and decided that a series of contour maps plus a table of information would provide the best format. The goal of the information phase of the project was to develop this series of maps and to tabulate the information from the drilling and testing for the landscape architect. Quantitative data sought to show overburden thickness, boundaries of the deposit and total minable thickness (both above and below water). The qualitative data needed to identify the proportion of sand, gravel and clay. The amount of clay (wash loss) was important for helping predict volumes of material that could be available for reclamation.

METHODS

For the 16 additional test borings a drill rig equipped with hollow stem augers was used. Samples were collected at five-foot intervals with a two-inch diameter split spoon sampler. Standard sieve analyses were run to determine not only the quality of material that would be available but also the amount of wash loss. Wash loss data usually only gives negative information, but in this case the volume of wash loss was considered in the reclamation plan.

During the drilling, the thickness of overburden and

Table 1. Tabulated drill hole data.

Hole No.	X Coord.	Y Coord.	Ground Elev.	Depth to Water	W.T. Elev.	OB Thick.	Deposit Top Elev.	S & G Thick	Deposit Bot. Elev.	Thick Above	Thick Below	
U 1	68	19	780	21	759	21	759	8	751	0	8	
U 2	73	27	801	15	786	8	793	24	769	7	17	
U 3	93	56	821	37	784	5	816	25	791	25	0	
U 4	77	58	818	38	780	5	813	73	740	33	40	
U 5	73	63	818	38	780	3	815	68	747	35	33	
U 6	70	68	819	37	782	2	817	46	771	35	11	
U 7	79	53	815	35	780	3	812	65	747	32	33	
U 8	83	48	814	31	783	2	812	59	753	24	35	
U 9	80	62	823	39	784	2	821	23	798	23	0	Becker
U 10	86	68	830	43	787	9	821	19	802	19	0	Drilling
U 11	75	54	815	31	784	2	813	47	766	27	20	1973
U 12	77	44	810	31	779	2	808	27	781	27	0	
U 13	78	37	807	40	767	2	805	28	777	28	0	
U 14	62	60	810	33	777	14	796	57	739	19	38	
MT 1	63	52	805	23	782	2	803	26	777	21	5	
MT 2	63	42	802	28	774	12	790	33	757	16	17	
MT 3	63	35	788	13	775	7	781	30	751	6	24	
A 14	90	26	805	20	785	1	804	33	771	19	14	
A 16	90	18	809	25	784	1	808	46	762	24	22	
B 11	86	38	807	21	786	1	806	40	766	20	20	
B 13	86	30	803	18	785	1	802	31	771	17	14	
B 15	86	22	803	23	780	1	802	41	761	22	19	
C 10	82	42	809	21	788	1	808	34	774	20	14	
C 12	82	34	795	10	785	1	794	16	778	9	7	
C 14	82	26	802	20	782	1	801	42	759	19	23	
C 16	82	18	802	24	778	8	794	38	756	16	22	
D 9	78	46	811	20	791	1	810	28	782	19	9	
D 11	78	38	806	20	790	1	805	24	781	19	5	
D 13	78	30	802	18	784	5	797	30	767	13	17	Sterling
D 15	78	22	800	21	779	10	790	30	760	11	19	Drilling
E 8	74	50	812	13	799	9	803	19	784	4	15	1974
E 10	74	42	806	20	786	4	802	24	778	16	8	
E 12	74	34	803	20	783	5	798	31	767	15	16	
E 14	74	26	801	23	778	13	788	25	763	10	15	
E 16	74	18	787	3	784	9	778	11	767	-6	11	
F 7	70	54	812	22	790	6	806	54	752	16	38	
F 9	70	46	805	19	786	1	804	33	771	18	15	
F 11	70	38	802	19	783	7	795	24	771	12	12	
F 13	70	30	801	19	782	14	787	16	771	5	11	
F 15	70	22	790	10	780	17	773	7	766	-7	7	
G 8	66	50	805	19	786	4	801	19	782	15	4	
G 10	66	42	799	11	788	8	791	13	778	3	10	
G 12	66	34	790	13	777	6	784	26	758	7	19	
H 6	62	58	809	23	786	3	806	24	782	20	4	
H 9	62	46	802	21	781	11	791	17	774	10	7	
H 11	62	38	798	13	785	15	786	10	773	-2	10	

Table 1. Continued.

Hole No.	X Coord.	Y Coord.	Ground Elev.	Depth to Water	W.T. Elev.	OB Thick.	Deposit Top Elev.	S & G Thick	Deposit Bot. Elev.	Thick Above	Thick Below	
I 8	58	50	801	13	788	9	792	19	773	4	15	
I 10	58	42	787	3	784	5	782	4	778	-2	4	
I 12	61	34	784	1	783	6	778	10	768	-5	10	
J 2	54	70	809	22	787	9	800	52	748	13	39	
J 4	54	66	806	17	789	9	797	44	753	8	36	
J 6	54	58	802	14	788	10	792	49	743	4	45	Sterling
J 7	54	54	796	4	792	4	792	9	783	0	9	Drilling
J 9	54	46	789	3	786	5	784	7	777	-2	7	1974
L 0	46	82	796	4	792	6	790	4	786	-2	4	
L 2	46	74	794	8	786	5	789	31	758	3	28	
L 4	46	66	790	2	788	4	786	32	754	-2	32	
L 6	46	58	786	4	782	3	783	45	738	1	44	
M 1	42	78	800	4	796	3	797	6	791	1	5	
N 2	38	74	787	4	783	2	785	29	756	2	27	
A 78	90	78	841	37	804	40	801	0	805	0	0	
B 50	86	50	811	20	791	3	808	55	753	17	38	
B 54	86	54	822	30	792	4	818	51	767	26	25	
B 60	86	62	825	35	790	3	822	27	795	27	0	
C 26	84	26	804	25	779	8	796	37	759	17	20	
C 78	82	78	834	30	804	20	814	5	809	5	0	
D 74	78	74	825	27	798	5	820	10	810	5	0	
E 42	74	42	806	24	782	4	802	31	771	20	11	West
E 78	74	78	819	15	804	30	789	0	789	0	0	Michigan
F 54	70	54	812	25	787	4	808	56	752	21	35	Drilling
F 74	70	74	823	29	794	30	793	0	793	0	0	1988
G 78	66	78	827	29	798	35	792	0	792	0	0	
J 65	54	66	806	20	786	7	799	53	746	13	40	
K 78	51	77	810	23	787	10	800	18	782	13	5	
M 96	43	94	816	25	791	13	803	15	788	12	3	

depth to water was recorded. The test results (sieve data) identified the thickness of salable material. The landscape architect had a topographic map of the property prepared at a scale of one-inch = 300 feet with a two-foot contour interval. A 100-foot x-y grid system was drawn onto this base map which then allowed each drill hole to receive an x, y and z coordinate value.

All of the drill data were tabulated according to the following column headings: drill hole number, x coordinate, y coordinate, ground elevation (z coordinate), top of deposit elevation, thickness of minable material, bottom of deposit elevation, minable thickness above water and minable thickness below water.

The x and y coordinate values were given to the nearest hundred. The development of the contour maps was done with a computer program: Surfer by Golden Software, Inc. Tabulated data was the base information for the Surfer program and each map required a separate table of x, y and z data. Tables were created and stored on a spreadsheet program (Lotus) and imported to the mapping program for the preparation of each map.

The deposit is classified as a glacial outwash deposit that somewhat parallels a modern river. These kinds of deposits consist of well sorted material. Moraines form the lateral boundaries of the outwash and erosion by the river influenced the salable aspects of the deposit. The drilling sought to find the boundaries of the deposit, both lateral and vertical, and to collect samples for analysis to find the range of potential products.

The x, y grid coordinate system relates past, present future drill hole locations with a common numbering scheme and it established a coordinate system for use in the computer graphics. The origin for the grid was placed to the south and west of the property to conveniently include all drill data. The letter designation proceeds from east to west and the number designation proceeds from south to north, I.E., the data sequence is from A-78 to M-96. Two earlier drilling programs had not been coordinated and suffered from different and confusing drill hole numbering schemes.

TABULATED DRILL DATA

The tabulated drill data include all current and past information. These data appear in chronological order with the Becker data first, the Sterling information next and the current data last. Table 1 has twelve columns, only a few of which need an explanation. The first column gives the number of test borings and the second and third have the x and y coordinates (given in 100's of feet from the origin). Ground elevation comes from the topographic map provided by the landscape architect. Depth to water is from the drill notes and the water table (W.T.) elevation is the subtraction of the two.

Columns "OB thick" (overburden thickness) and "S & G thick" (sand and gravel thickness) likewise came from the drill data. Top of deposit elevation merely subtracts the overburden thickness from the ground elevation and the bottom of deposit subtracts both the overburden and sand thicknesses from the ground elevation. Columns "Thick Above" and "Thick Below" signify the amount of minable material above the water table and the amount below. The far right side of the table gives the drillers name and year in which the drilling took place.

COMPUTER MAPS

Eight computer generated maps appear in the following sequence:

1. TEST BORING LOCATIONS AND MINING BOUNDARIES
2. GROUND SURFACE ELEVATIONS
3. WATER TABLE ELEVATION MAP
4. OVERBURDEN THICKNESS
5. DEPOSIT THICKNESS
6. THICKNESS ABOVE WATER
7. THICKNESS BELOW WATER
8. BOTTOM OF DEPOSIT ELEVATIONS

Each is at a scale of one inch = 100 feet and shows the roads, test boring locations and deposit boundaries.

The deposit boundaries are shaded on Figure 1 for easy identification and each segment of the property shows the acres and the estimated tons in place for that segment. The boundaries include 100-foot setbacks from the roads and adjacent properties (including the railroad). Straight lines were chosen for the northern and western boundaries to speed the computer graphics. However, the actual boundaries are not likely to be as straight as depicted. The boundaries and roads appear on all of the other maps but have not been labelled because the labels would interfere with the significant information on these subsequent maps.

Figures 2 through 8 are contour maps, where contour lines represent positions of equal elevation or equal thickness. These maps were generated through a computer software program (Surfer by Golden Software of Denver). It uses elevation or thickness information from each of the 72 holes plotted. there are a total of 76 holes but three are duplicates (E10 = E42, F7 = F54 and J4 = J65) and one was a shallow monitor well. The software program allows the data to interact such that the contour lines in the center of the maps had the benefit of all of the surrounding data. On the other hand those contour lines near the edges had less information with which to interact, so are more subject to error. This variation in map accuracy is clear when comparing the Ground Surface Elevations (Figure 2) with the topographic map provided by the landscape architect. The northern and eastern boundaries show the most deviation from the surveyed map but the rest of the map shows a very good correlation between the two.

Figure 3 shows that there is not a great deal of variation in the water table, which is to be expected. The water table elevation is generally highest to the northeast and falls toward the river. It tends to follow the surface contours.

Figures 4 through 7 are also isopach maps which show variations in thickness of material. Figure 4 illustrates the differing thicknesses of overburden. the contour interval is five feet. There is a large area where the overburden is five feet or less (the Highway and south of Staib Road). Figure 5 is a similar illustration for the minable material. This map shows that the deposit is thickest near the junction of Staib Road and the Highway. It also shows two thick zones that extend west of the suggested mining boundary: one north of Staib Road and one to the south. The company should be able to mine to the flood plain boundary but should not mine into the flood plain. Figures 6 and 7 merely show the amount of minable material above and below the water table. The landscape architect used these maps for reclamation and mine planning as an aid to know what technique may be best suited for underwater mining.

Figure 8 shows what the topography might look like if all of the material were removed. This map also helped guide how and where to distribute overburden and fines to create the greatest amount of usable land.

PLANNING CRITERIA

The deposit is the structure upon and within which all planning decisions, related to mining and land development, are derived. Equally significant is the fact that mining operations provide the tools necessary to implement the planning decisions. Included in this process are, of course, consideration for regulations, local planning, environmental issues and community relations. However, the focus of this paper is the relationship between the deposit and mining and land development procedures.

Contrary to common perceptions, land is not destroyed by the aggregate mining process. It is simply altered; sometimes very dramatically. The deposit outline, overburden, water table and land remain in the wake of the mining activity. All the ingredients for creating new and productive lands continue to be present in these mine sites. To succeed in developing the proposed mine site to its fullest potential, it was determined that four basic criteria must be set.

First, planning activities must occur before mining is initiated to assure that available resources are fully utilized and that the site can be developed to its fullest potential.

Ideally, as in the case of this project, it should occur as part of the deposit investigation and operation planning;

Second, the process of land shaping must be an integral part of the mining operation to assure economy of earth moving;

Third, the economy of the mining operation cannot be disrupted by the land shaping activity. One consequence would be that the mining company will ignore that particular activity because it will interfere with efficient mining practices; and

Fourth, both land shaping and mining operation decisions must relate to and be derived from the character and elements of the deposit.

Information about the deposit was critical in making decisions about reducing the visual and audio impacts related to both the extraction operation and processing plant. The site is flat and fully exposed to the surrounding lands. Therefore, one of the key bits of information was the depth of the deposit to the water table. The depth ranged from 12 to 20 feet. This factor was influential, for example, in the decision to select a dredge rather than a dragline to excavate the aggregate. The dragline operates at the existing surface and would be fully exposed throughout the life of the mining operation, while the dredge operates on the water, below the surrounding terrain, and, therefore, out of sight from adjacent lands. Also, as a result of this "below grade" excavation, sound generated by the operation would be reduced.

PLANNING STEPS

With the completion of the various computer maps described above, information was consolidated into a series of graphic maps that illustrate the patterns of deposit characteristics (Figures 9-12). These graphics set the stage for determining the pattern of excavation, the location of proposed overburden fill areas to build new lands, location of the processing plant and the final proposed land form. The first step in this process involved overlaying a 200 foot grid over the entire site. Then, values were assigned to each grid for each type of map, based upon the interpretation of the isopachs, boring logs and other data provided by the geologist. For example, in Figure 10 - TOTAL DEPOSIT DISTRIBUTION, the grid contained six values indicating various deposit depths. These values ranged from a low of 0 to 10 feet to a high of 51 to 70 feet. During the initial planning stages an average number was assigned to each 200 foot grid. Later, during the final stages, more precise earth volume calculations were conducted.

Following completion of this step, basic planning parameters were established to guide the planning process. These included the determination of:

Types and characteristics of earth moving equipment and earth moving procedures;
Maximum earth hauling distance, particularly in regard to the redistribution of the overburden;
Requirements and procedures for the reduction of visual and audio impacts on the surrounding lands;
Access requirements to, from and within the site; and
Type of processing plant, space requirements of the plant and the visual characteristics of the plant.

The integration of these parameters with deposit characteristics then provided the basis for development of the long range mining and reclamation program.

PLANNING OBJECTIVES

The objectives of this pre-mine planning program were to:

Maximize development of the aggregate resource;
Maximize the land/water development potential of the mined-out site;
Maximize use of overburden and waste sand (fines) in creating useable and productive land and water areas;
Establish an aggregate extraction pattern that would benefit both the mining and land shaping operations; and
Reduce visual and audio impacts of operations on surrounding lands.

Accomplishment of these objectives are best realized through the development of accurate deposit information. Based upon data developed by the geologist, the landscape architect was able to make a variety of land shaping, mining operational and environmental decisions about the site for the long range mining and reclamation plan.

PLANNING PROCEDURE

USE OF DEPOSIT DATA IN THE PLANNING PROCESS

Overburden is one of the most important land shaping elements available in a land reclamation program. It is essential to record the quantity, distribution and type of overburden that is available for building berms for screening and land for development (Figure 9). Depth of overburden in relation to the deposit depth needs to be correlated to determine the economic feasibility of extracting the reserves. For example, a general rule of thumb in the aggregate industry for determining the feasibility of extraction is that the ratio of deposit material should not exceed one foot of overburden to ten feet of reserves. Data from the borings, isopach maps, soil conservation service maps and field checks were used to develop Figures 9 and 12.

For determining the extent and pattern of excavation, the distribution, character and depth of reserves were delineated (Figure 10). This information identified the best and poorest areas for mining. To identify the best land development sites within the proposed mined-out area, information about the distribution, depth and character of overburden was delineated along with depth of reserves below water table (Figure 11). This information also influenced decisions related to the pattern of excavation and was essential in the effort to plan the integration of both the mining and the land shaping activities into a sequential and continuous mining operation. As a part of this process it was also necessary to determine the type of earth moving equipment that was to be used in both the overburden stripping and aggregate extraction operations.

DESCRIPTION OF DOCUMENTS

A total of thirty two sheets of maps and illustrations were prepared for the project. The major areas covered by these documents were, surface conditions, visual and regulatory issues, operations and site design details. They were developed in collaboration with the geologist and client to meet local, state and national regulatory requirements. They were also developed for the purpose of communicating to public officials and local citizens the complex and comprehensive approach taken by this particular mining company to undertake a responsible and sensitive long range mining and reclamation program, in which the community would have continuous input. The following seven maps were selected from the set of documents because they illustrate the connection between the geologic data, the basic planning process, the proposed mining operation and the end use concept. The seven maps are:

9. OVERBURDEN DISTRIBUTION
10. TOTAL DEPOSIT DISTRIBUTION
11. DEPOSIT DISTRIBUTION BELOW WATER
12. DEPOSIT/OVERBURDEN RATIO
13. SITE SELECTION: PROCESSING PLANT
14. GENERALIZED MINING SEQUENCE
15. MASTER SITE PLAN

Figures 9-12 involved the synthesis of information provided by the geologist. They illustrate the patterns of various deposit characteristics. In Figure 9 the shallowest overburden (0-3 feet) is illustrated by the white pattern, while the deepest areas of overburden (21-40) are indicated by the darkest tone. Given limits on hauling distances, a visual picture can be established as to where the overburden might best be distributed for land shaping purposes or where the overburden might be excavated to create any required berms for screening purposes. A clearer picture of where the overburden should be placed can be formed with an evaluation of Figure 11. This map shows the various depths of reserves below the water table. The lightest areas on the map indicate the shallowest below water reserves (0-5 feet), with the darkest patterns indicating where the deepest below water reserves (31-40 feet) are located. Given a choice of where to place the overburden to build the most useable land, it is obvious that the material should be deposited in areas of the site that have the shallowest water after mining is completed. Thus the land form pattern of the final reclamation plan can be, to a great extent, determined from the data provided by the geologist, long before mining is initiated.

Figure 13 illustrates a site selection study for the proposed processing plant. Five criteria were used to determine the best location. These included, accessibility to both the reserves and transportation routes, screening potential, potential deposit loss resulting from placement of the permanent plant, relation to the center of the aggregate reserve mass and land forming potential due to deposition of a large volume of fines that had to be deposited near the plant. In addition to information about the operations, three types of deposit information were assessed in determining the location and siting of the processing plant. These included depth of reserves to water table, depth of reserves below water and distribution of reserves. The information was used to site the permanent processing plant in a location that will be; (1) below the surrounding grade (after a portable plant would be used in the initial phase), (2) in a part of the site where little aggregate reserve exist below the water table, and (3) in a portion of the site that represented the approximate center of the reserve mass (Figure 13), thus reducing hauling costs between the pit and the processing plant.

Figure 14 illustrates the assimilation and synthesis of all the above describe data and determinations. It could be completed only after:

1. The structure of the deposit and its reserve patterns were clearly mapped;
2. The quantity and distribution of overburden was known;
3. The location of future mined-out areas most suitable for creating usable land was identified;
4. The location of the processing plant was set;
5. The type of earth moving and excavation equipment were selected for the operation;
6. The operational and development parameters were set.

Figure 14 illustrates the proposed sequence of mining and reclamation activity. It is divided into five phases that indicate the order in which the mining/reclamation sequence is to occur. Phase I and IA involves "opening the pit". A portable plant is used and a "hole" is excavated to five feet above water table. When this "hole" is completed, the permanent processing plant is installed. In the mean time, mining is extended across the road to open the pit in that portion of the site. It is important to note, all overburden located in phase I and IA areas is proposed to be used to create visual berms. This is to be the only overburden in the entire site that will not be placed directly into proposed land form areas. ALL OVERBURDEN IS TO BE PLACED INTO PRE-DETERMINED LOCATIONS TO AVOID DOUBLE HANDLING. The mining will be extended in an easterly direction toward the area of the deposit that has relatively shallow below-water reserves (see Figure 11). As a result, areas designated as potential new land forms will be available for the placement of the overburden. Phase II extends along the shallow part of the deposit (see Figure 11) where all the remaining overburden from the site east of the road will be deposited. It will then extend into the deepest portions of that part of the site identified as Phases II and III, before it proceeds back across the road to the area south of the processing plant. This process will then continue into Phases IV and V. In each phase mining begins in the shallow deposit to create a place for the deposition of the overburden and, therefore, land development.

Figure 15 illustrates one possible scheme for the development of the proposed mined-out site. The significant feature of this plan is that is a mirror image of the deposit structure. Review of Figures 10 and 11 indicates the correlation between the deposit patterns and the final proposed land forms.

CONCLUSION

The interaction between the geologist and landscape architect in the preparation of long range mining and reclamation plans is essential. The quality of planning decisions can only be as good as the quality of the geologic data upon which those decisions are made. The ultimate configuration of the reclaimed is a direct reflection of the deposit configuration. It is essential to have a thorough picture of the deposit configuration in order to assure that the site can be developed to its fullest potential, during and upon completion of the mining activity.

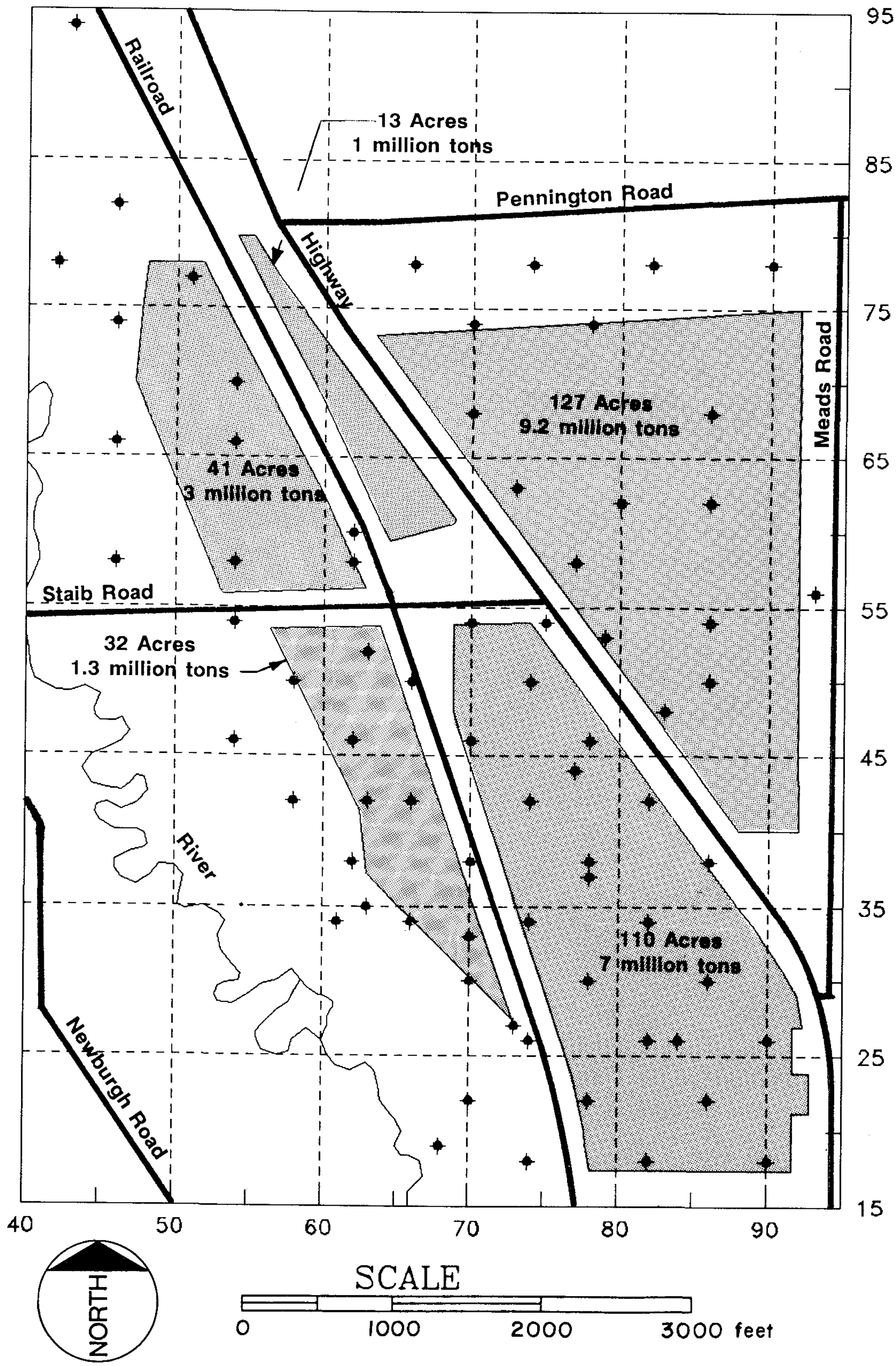


Figure 1. Test boring locations and mining boundaries.

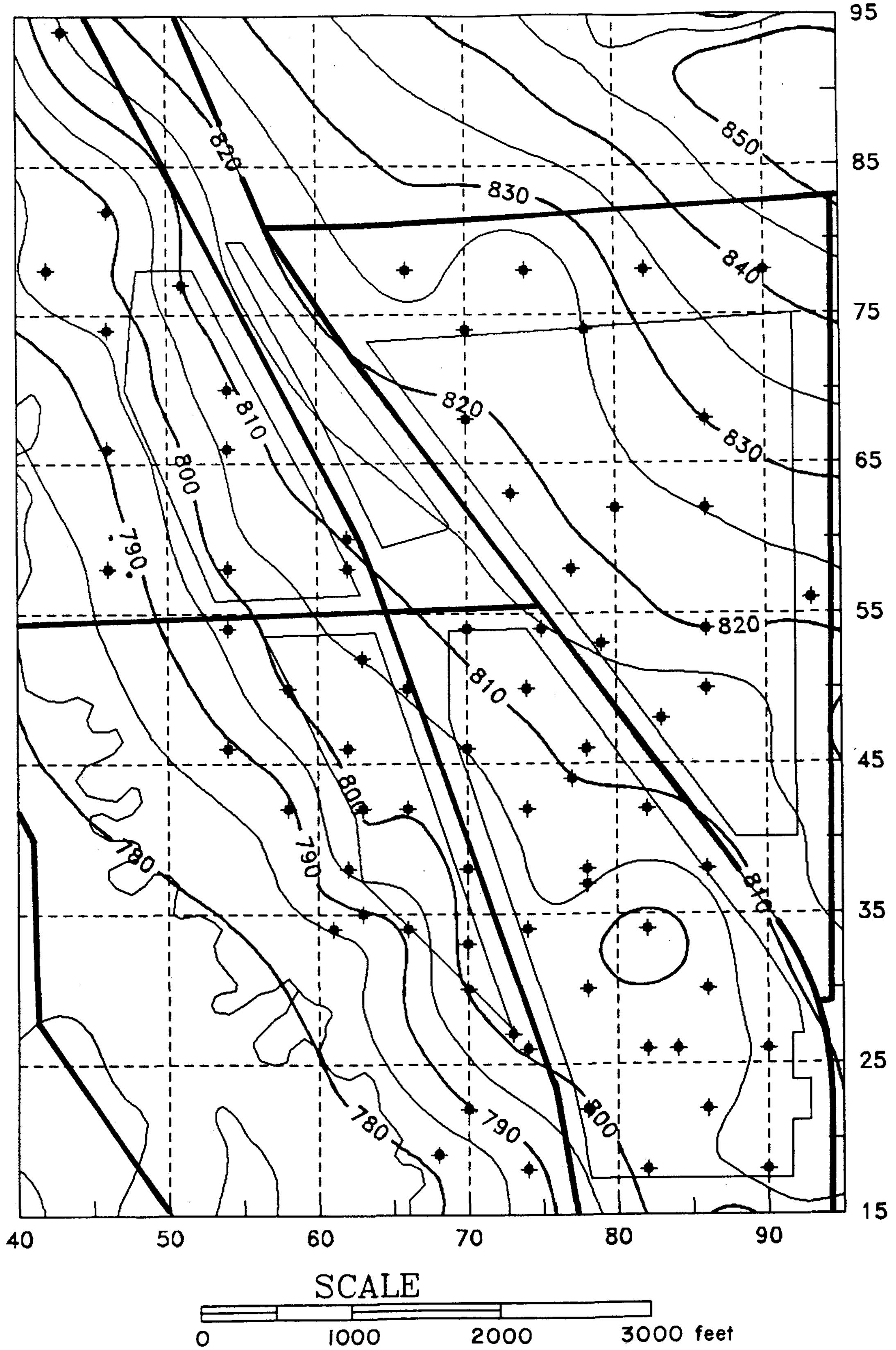


Figure 2. Ground surface elevations.

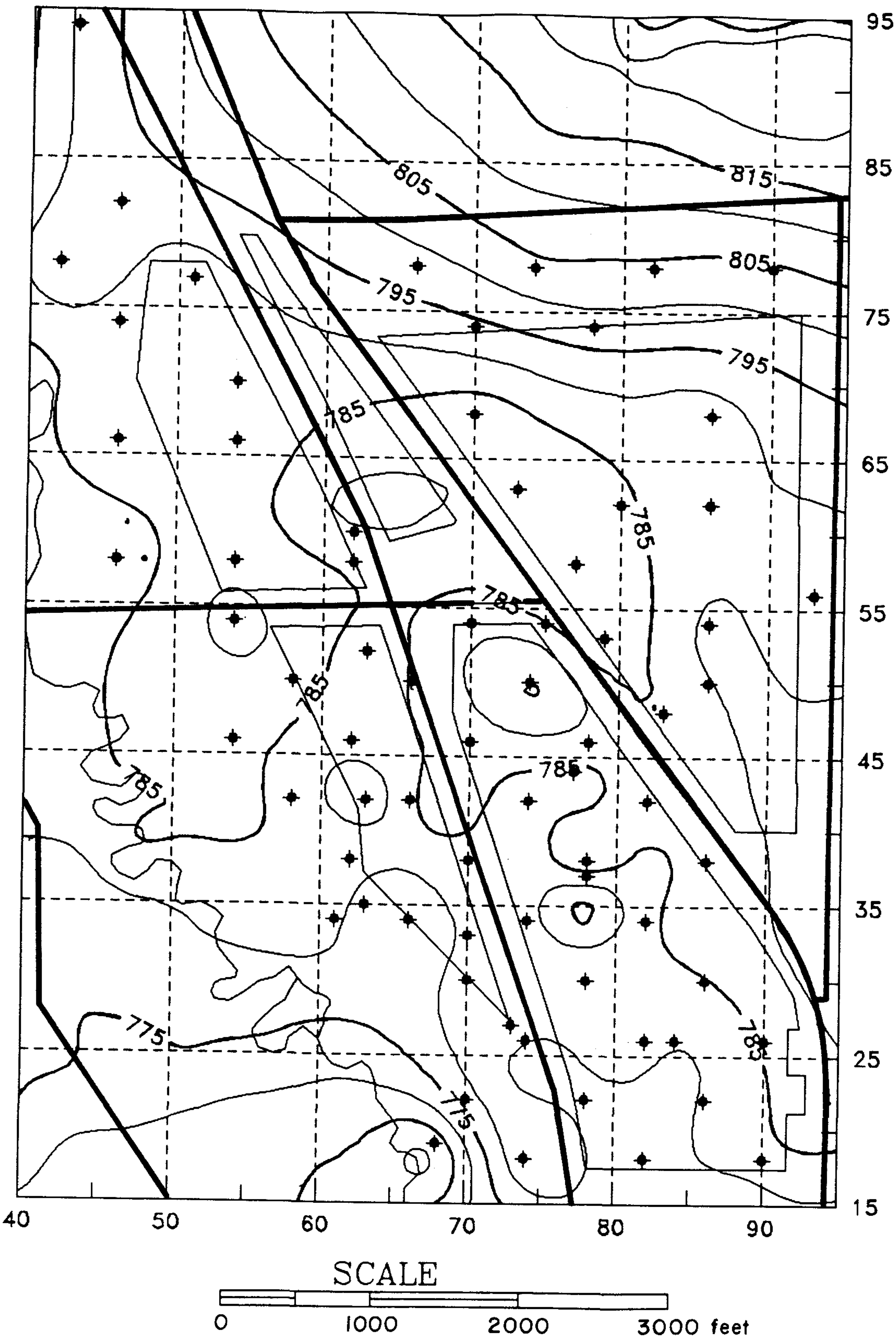


Figure 3. Water table elevation map.

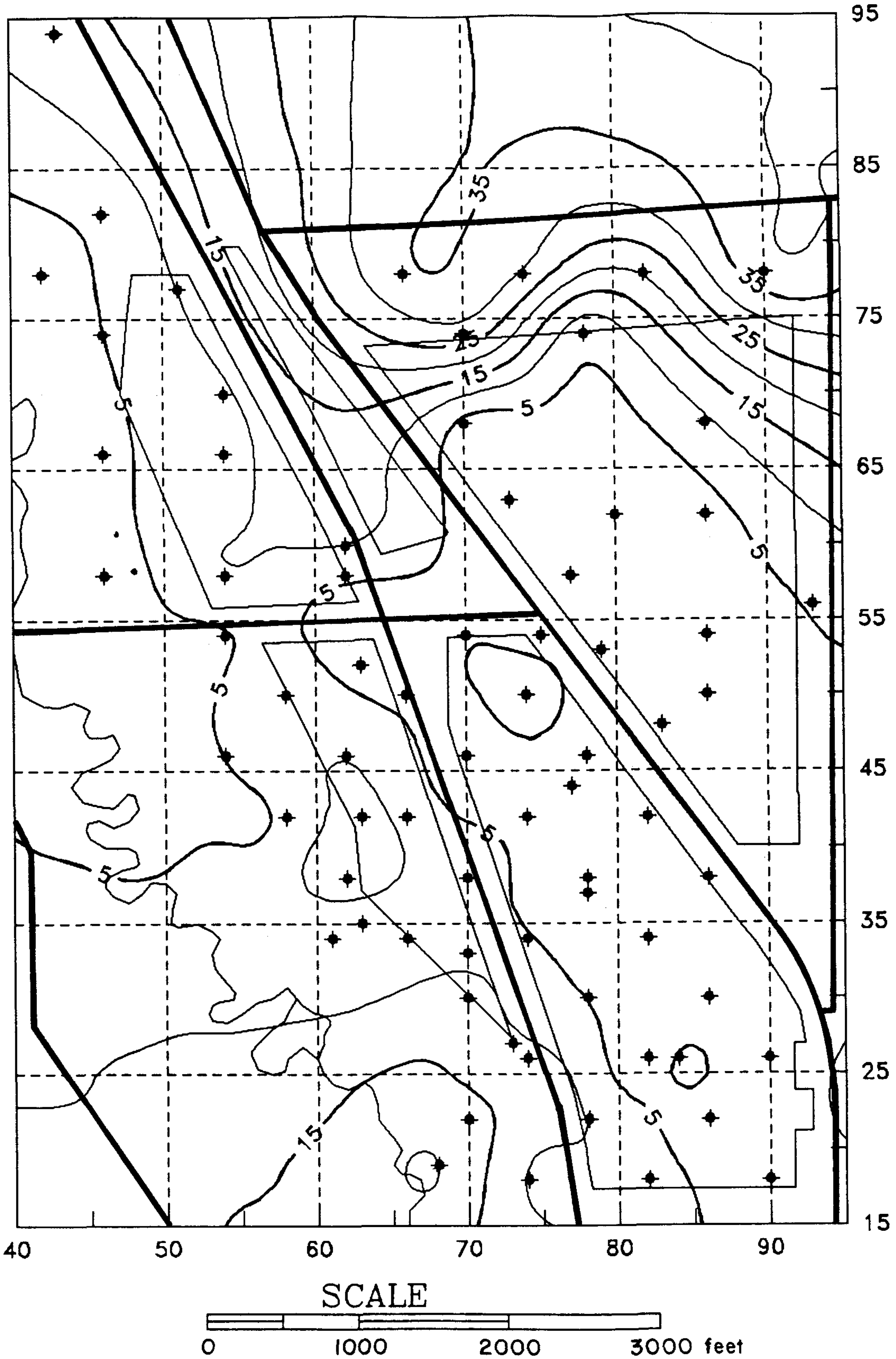


Figure 4. Overburden thickness.

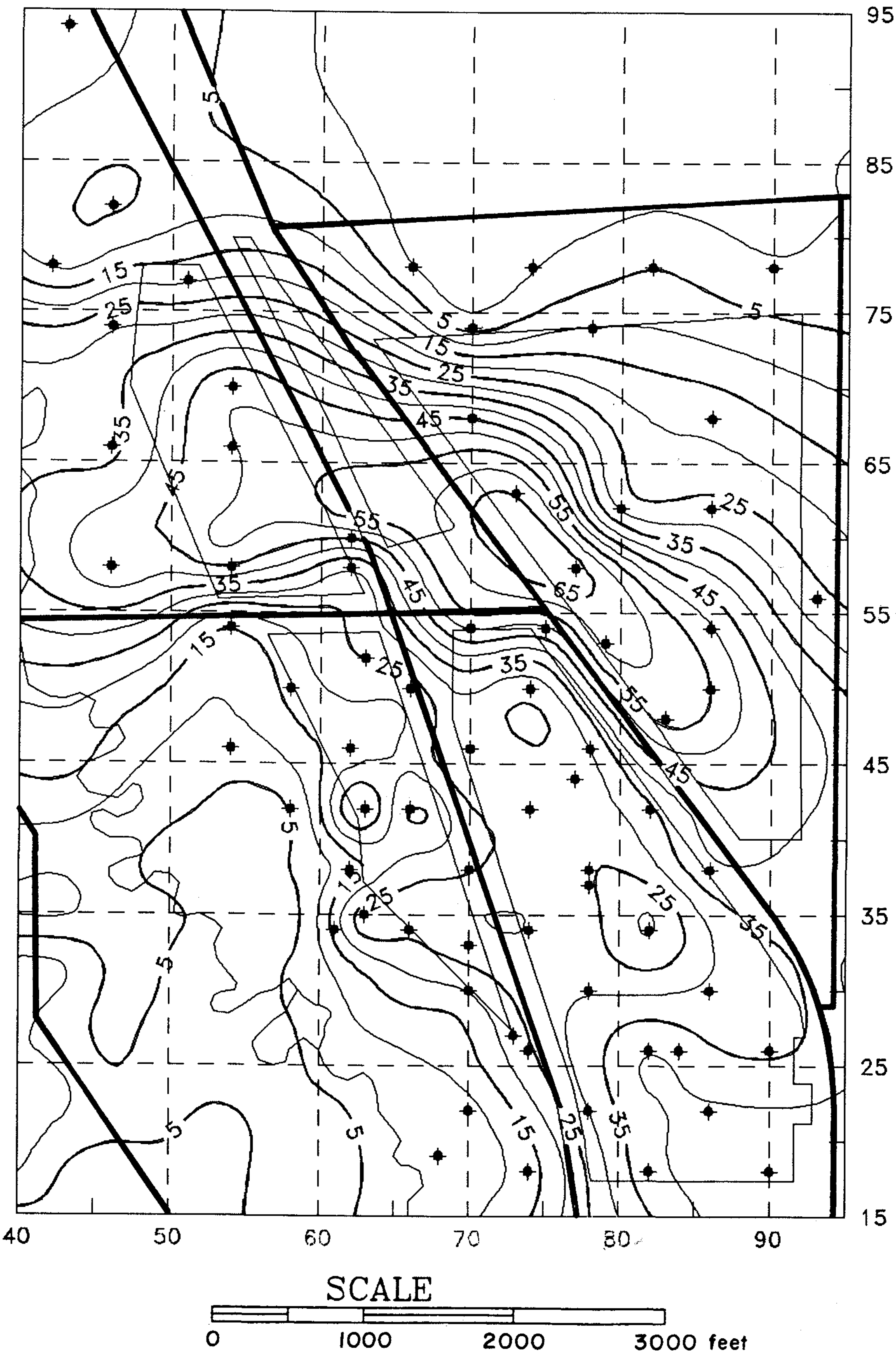


Figure 5. Deposit thickness.

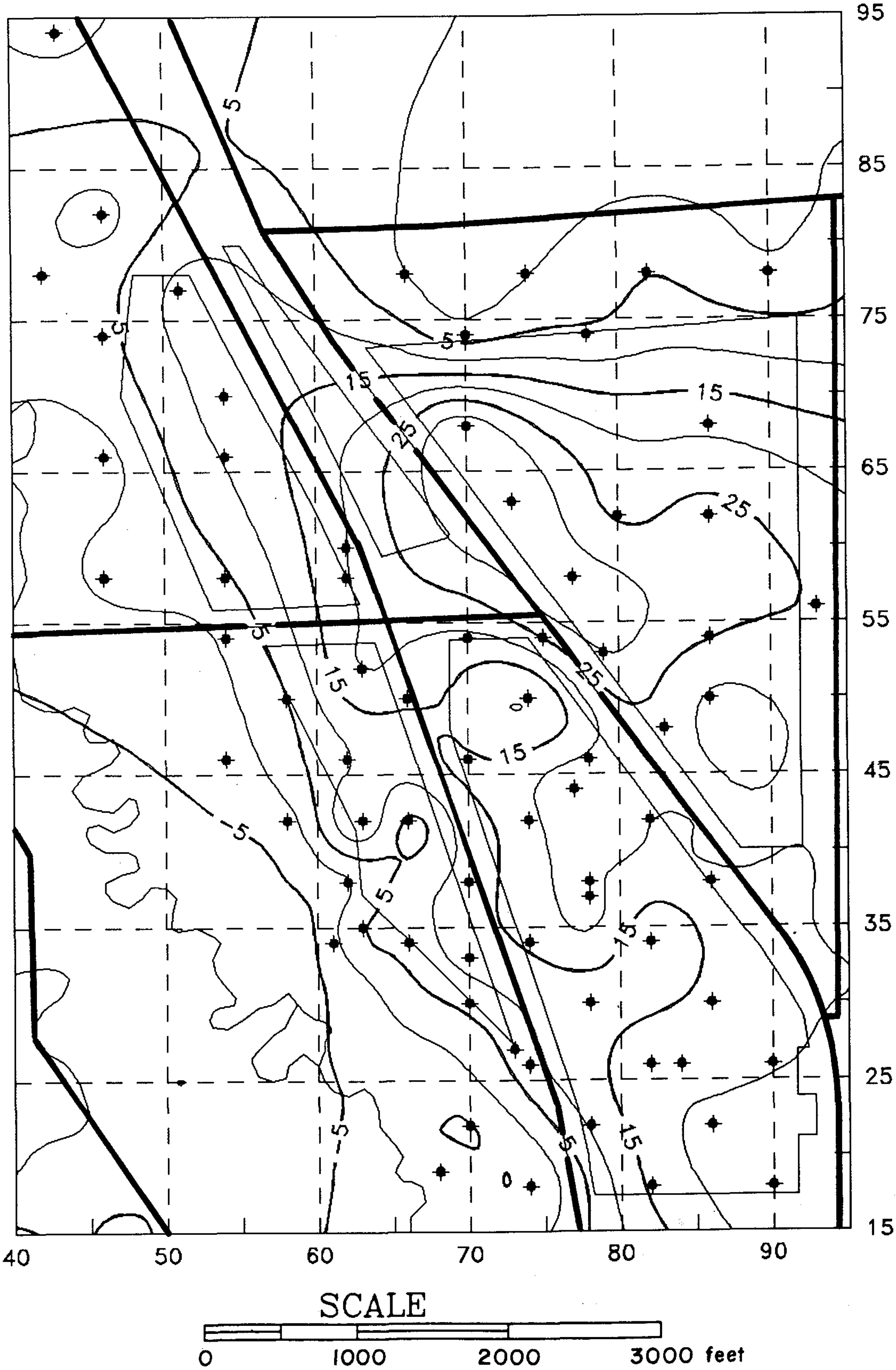


Figure 6. Thickness above water.

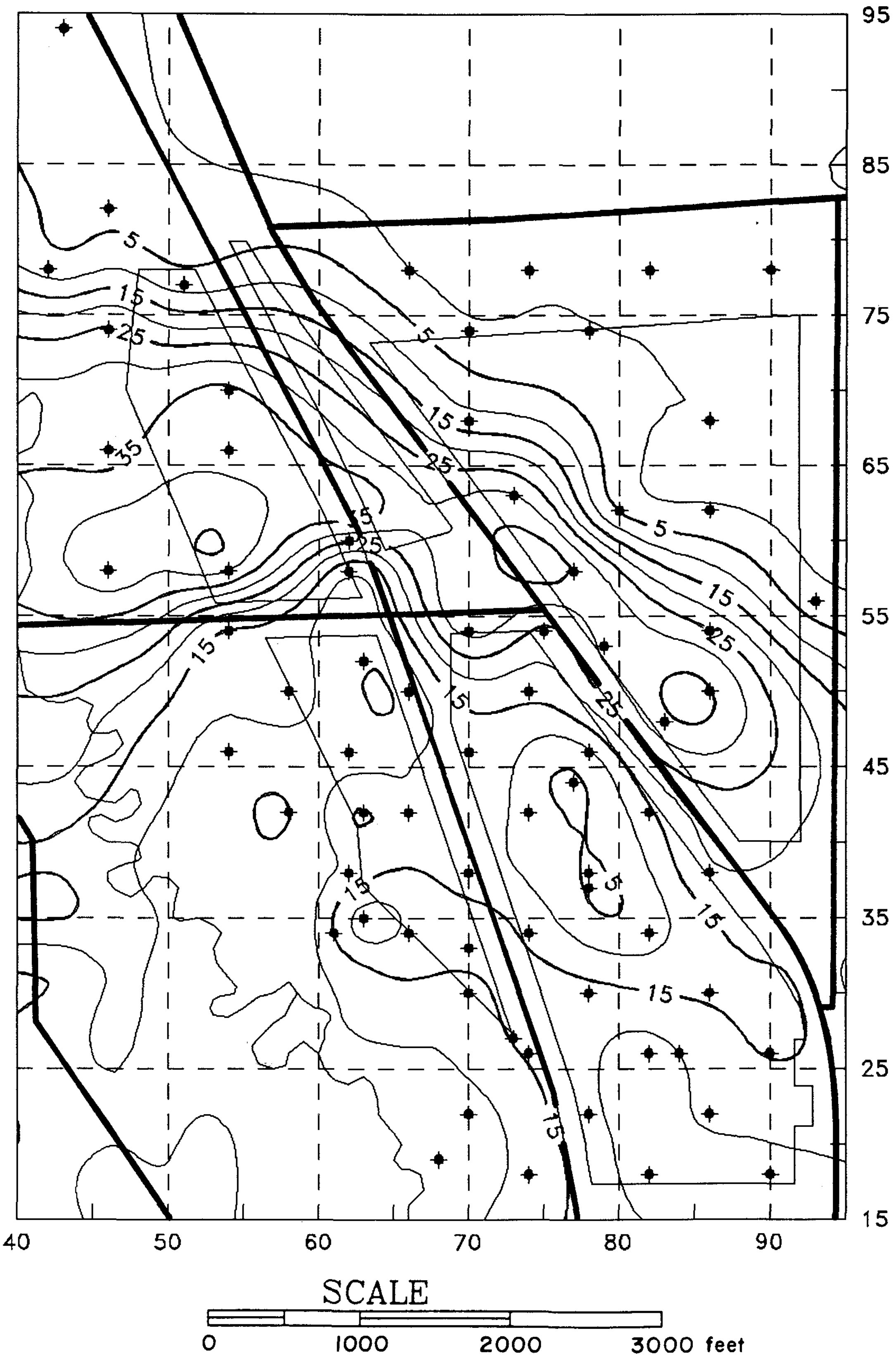


Figure 7. Thickness below water.

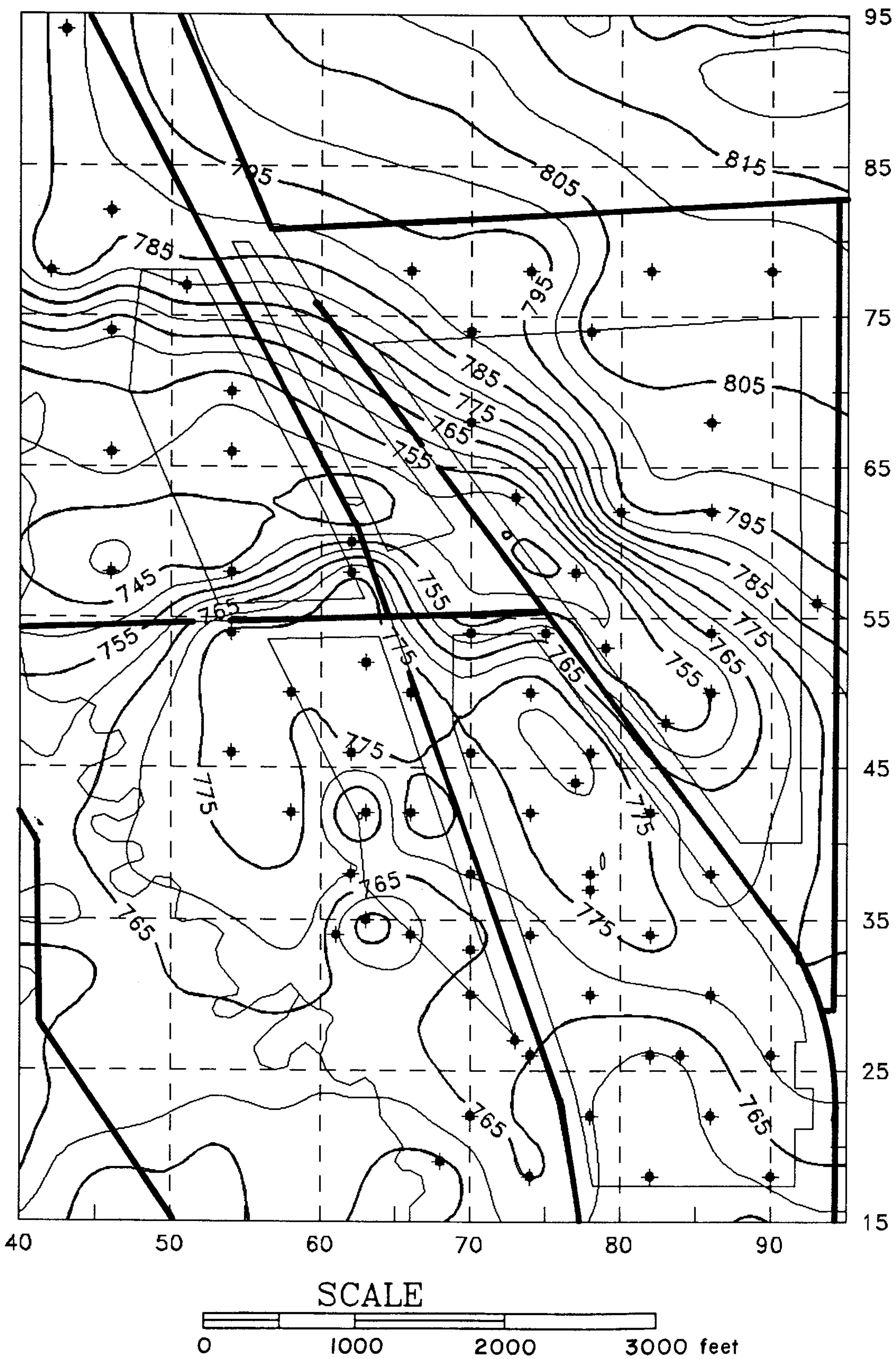


Figure 8. Bottom of deposit elevations.

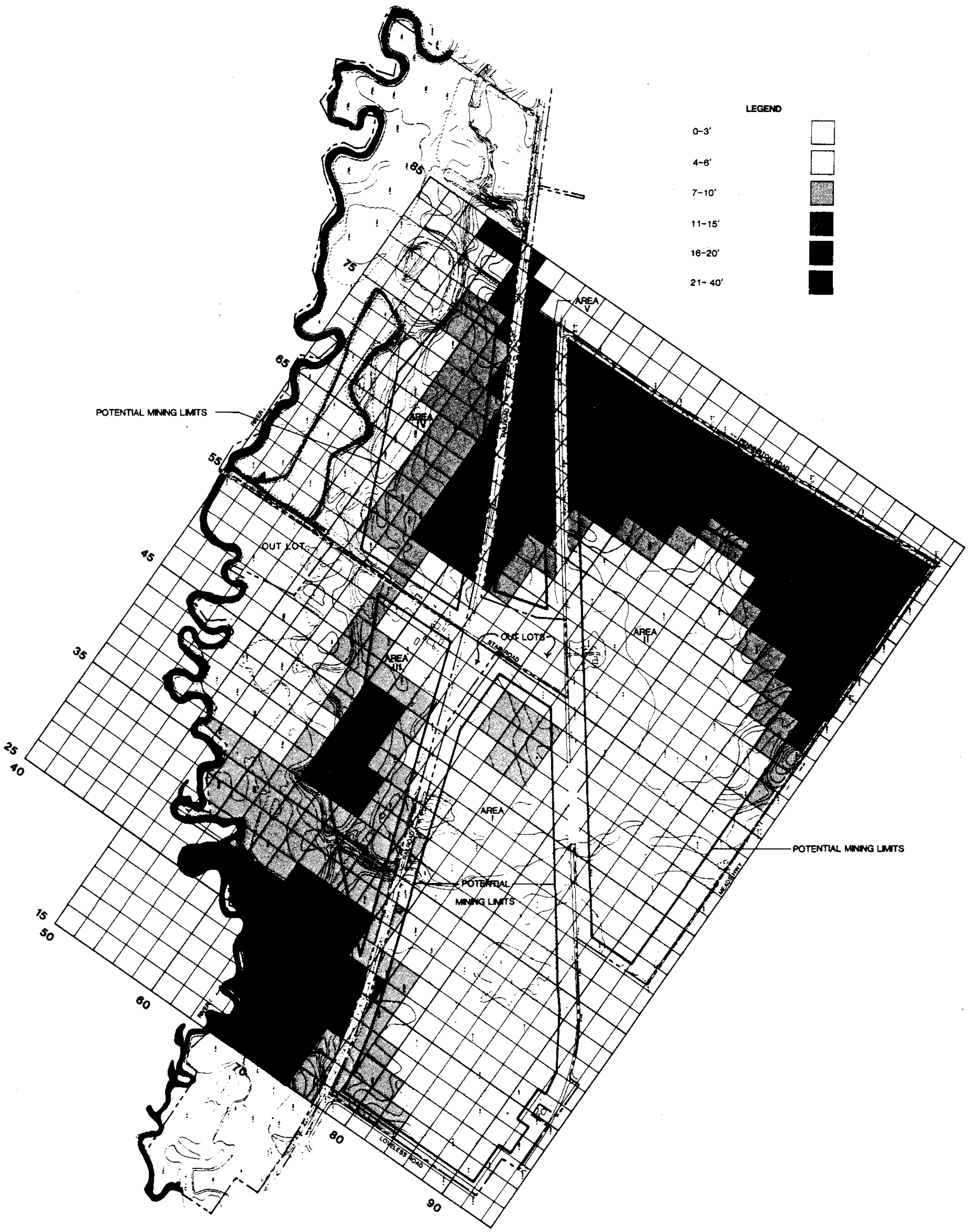


Figure 9. Overburden distribution.

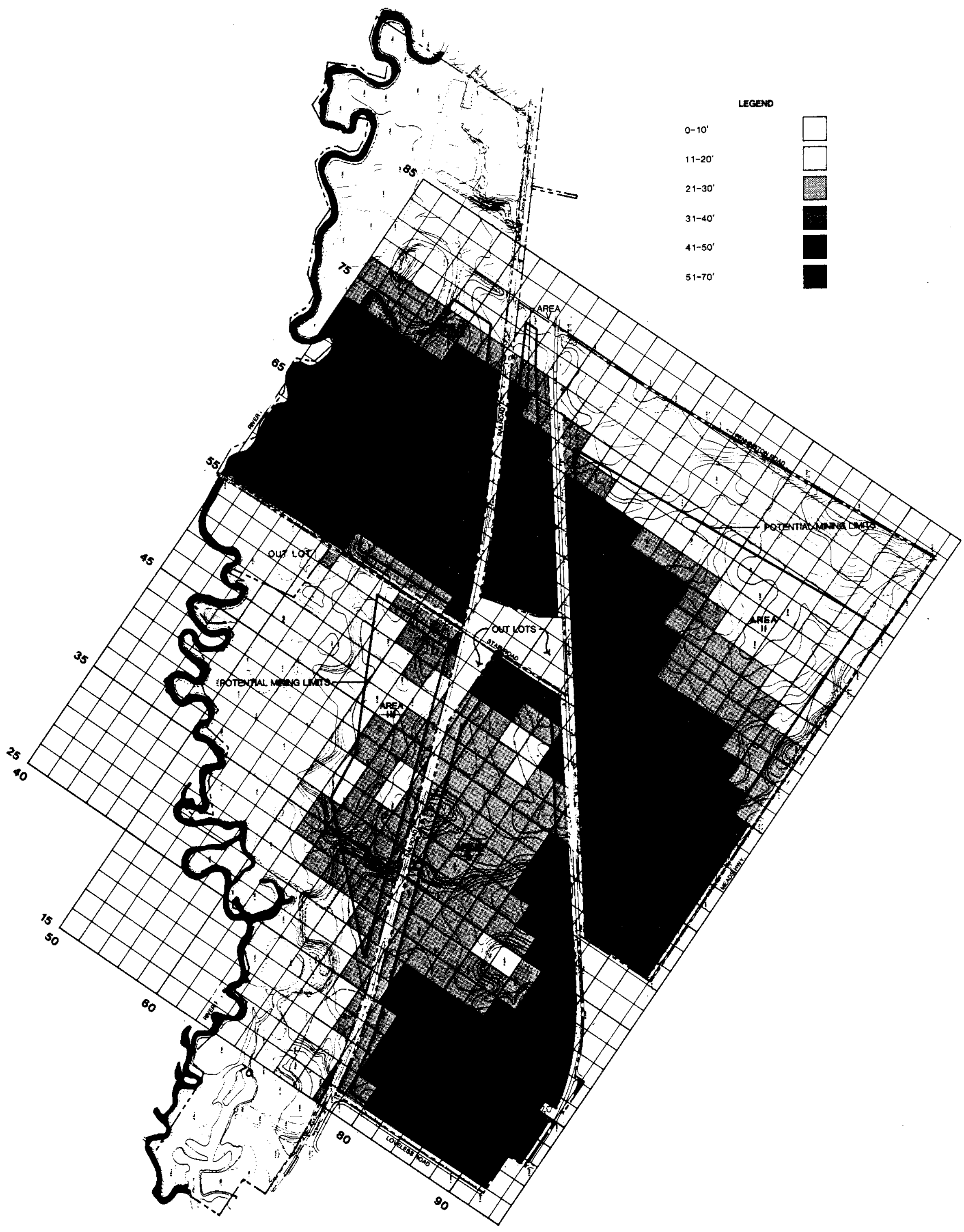


Figure 10. Total deposit distribution.

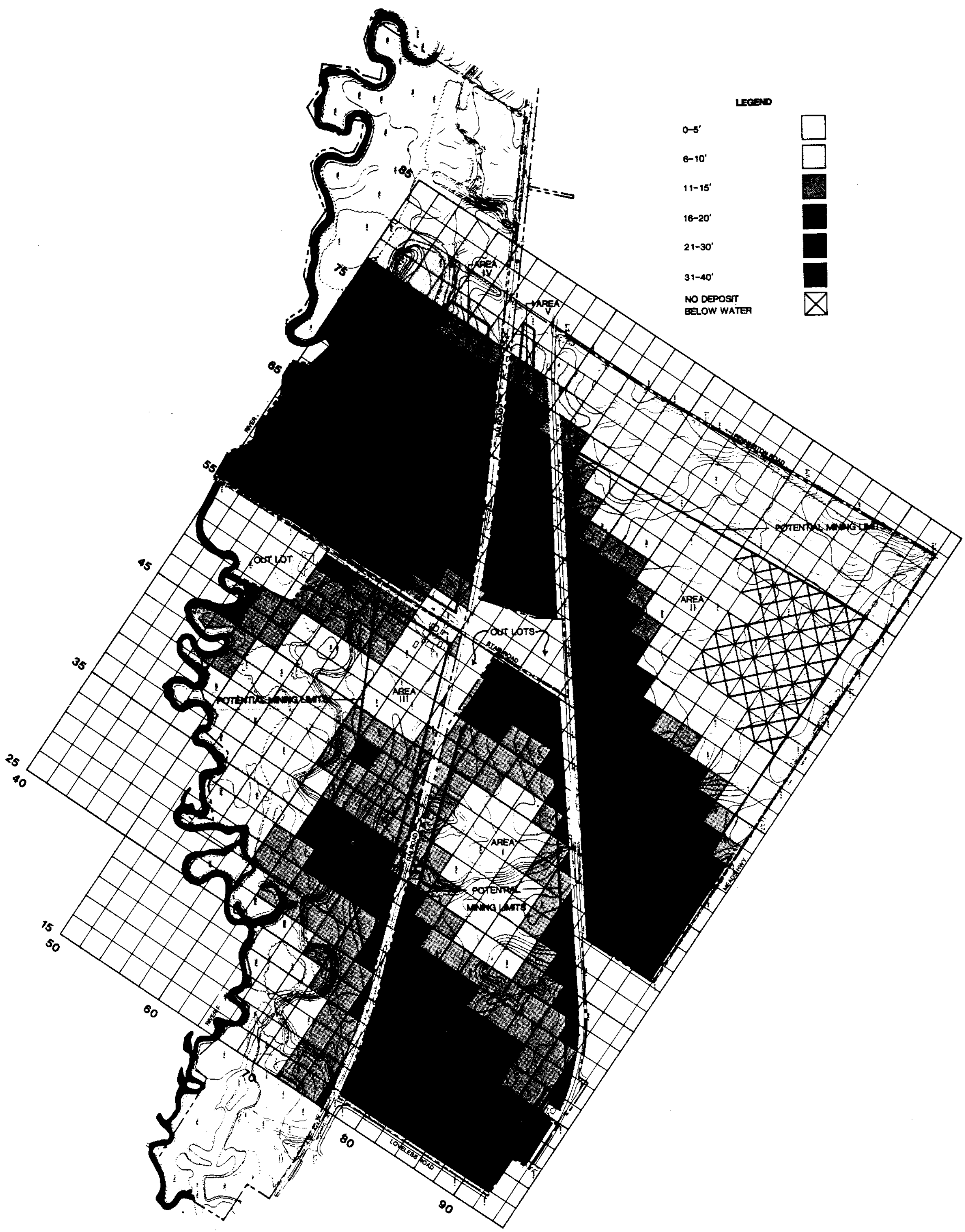


Figure 11. Deposit distribution below water.

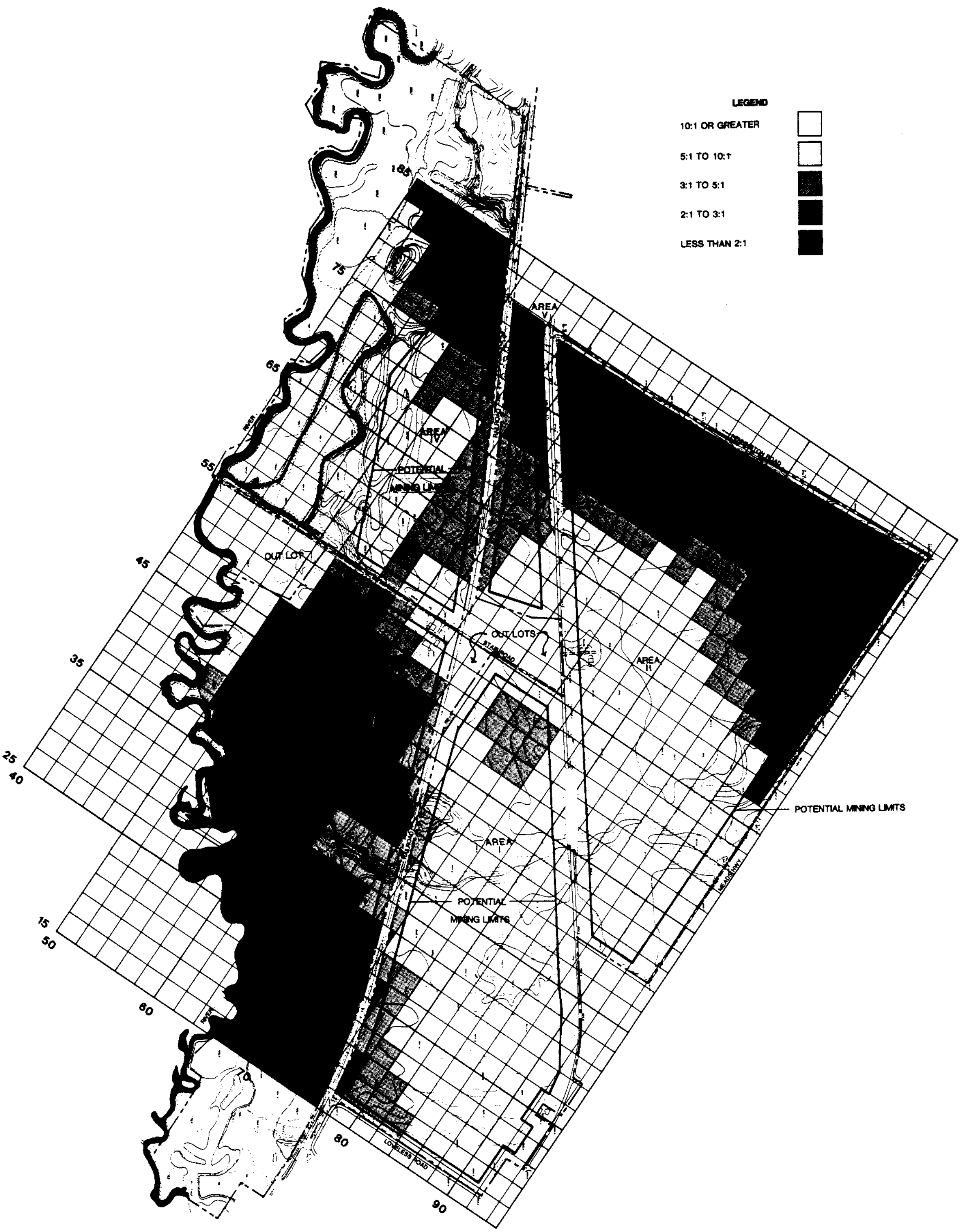
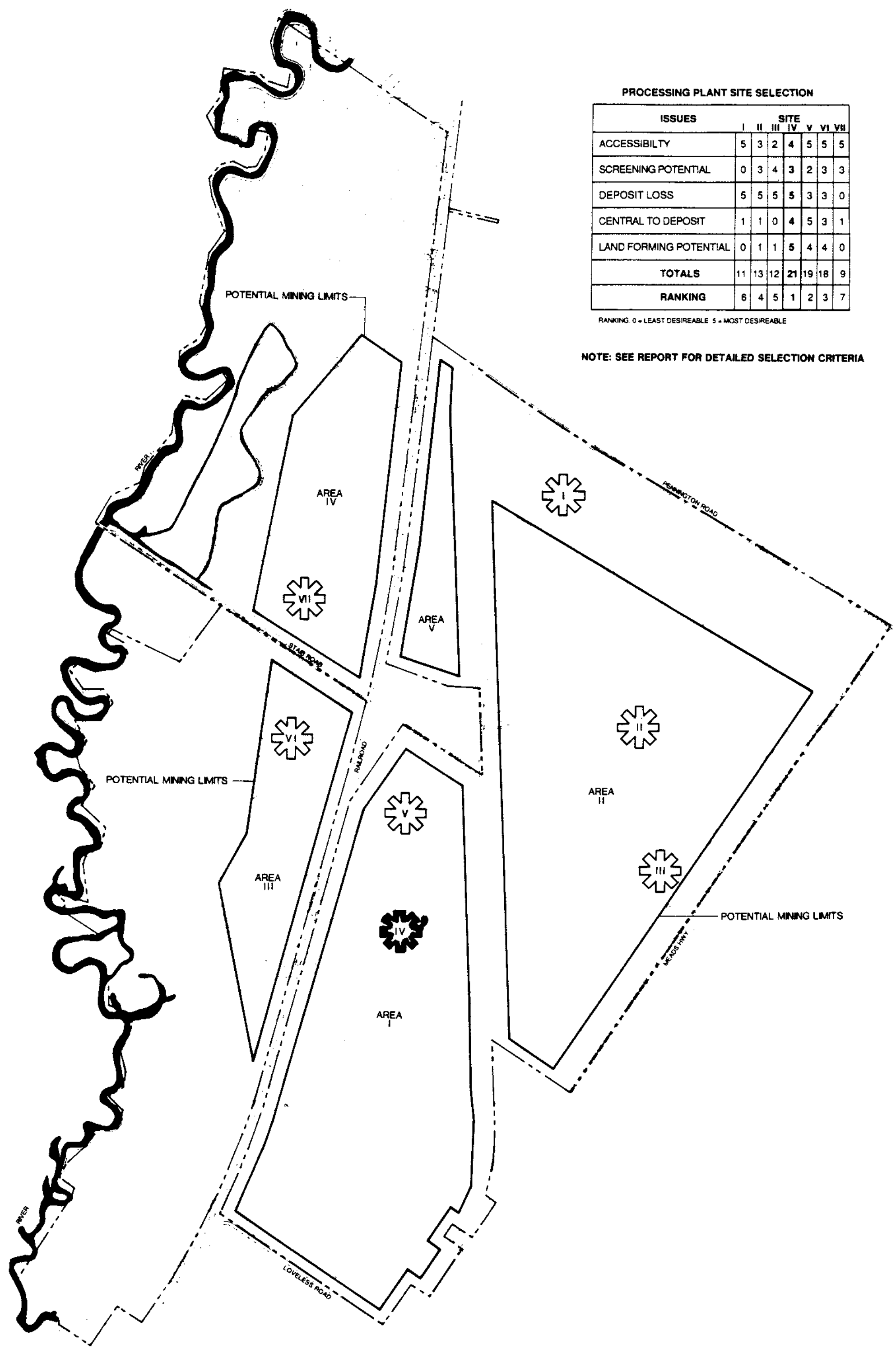


Figure 12. Deposit/overburden ratio.



PROCESSING PLANT SITE SELECTION

ISSUES	SITE I	II	III	IV	V	VI	VII
ACCESSIBILTY	5	3	2	4	5	5	5
SCREENING POTENTIAL	0	3	4	3	2	3	3
DEPOSIT LOSS	5	5	5	5	3	3	0
CENTRAL TO DEPOSIT	1	1	0	4	5	3	1
LAND FORMING POTENTIAL	0	1	1	5	4	4	0
TOTALS	11	13	12	21	19	18	9
RANKING	6	4	5	1	2	3	7

RANKING. 0 = LEAST DESIREABLE 5 = MOST DESIREABLE

NOTE: SEE REPORT FOR DETAILED SELECTION CRITERIA

Figure 13. Site selection: processing plant.

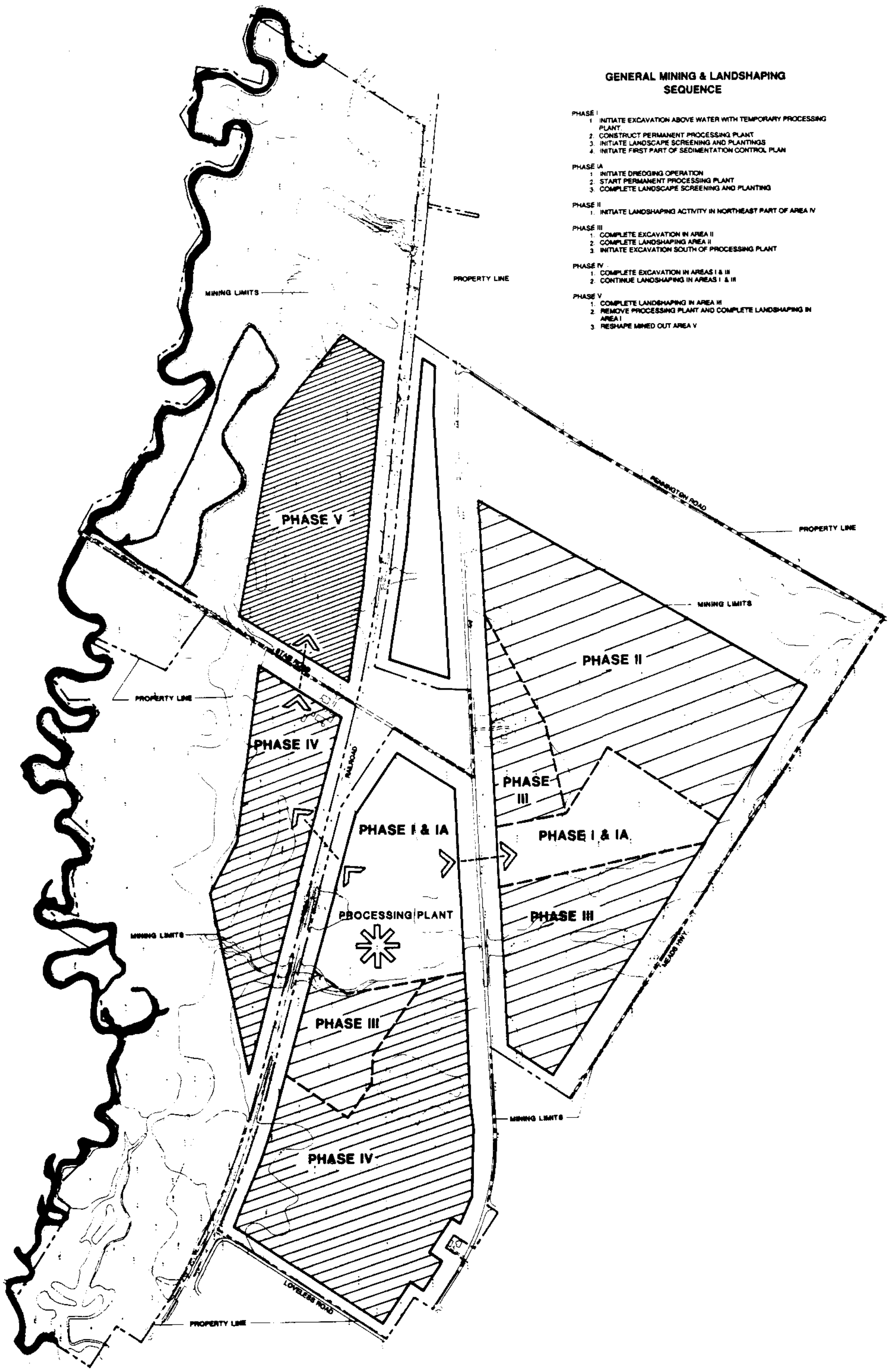


Figure 14. Generalized mining sequence.

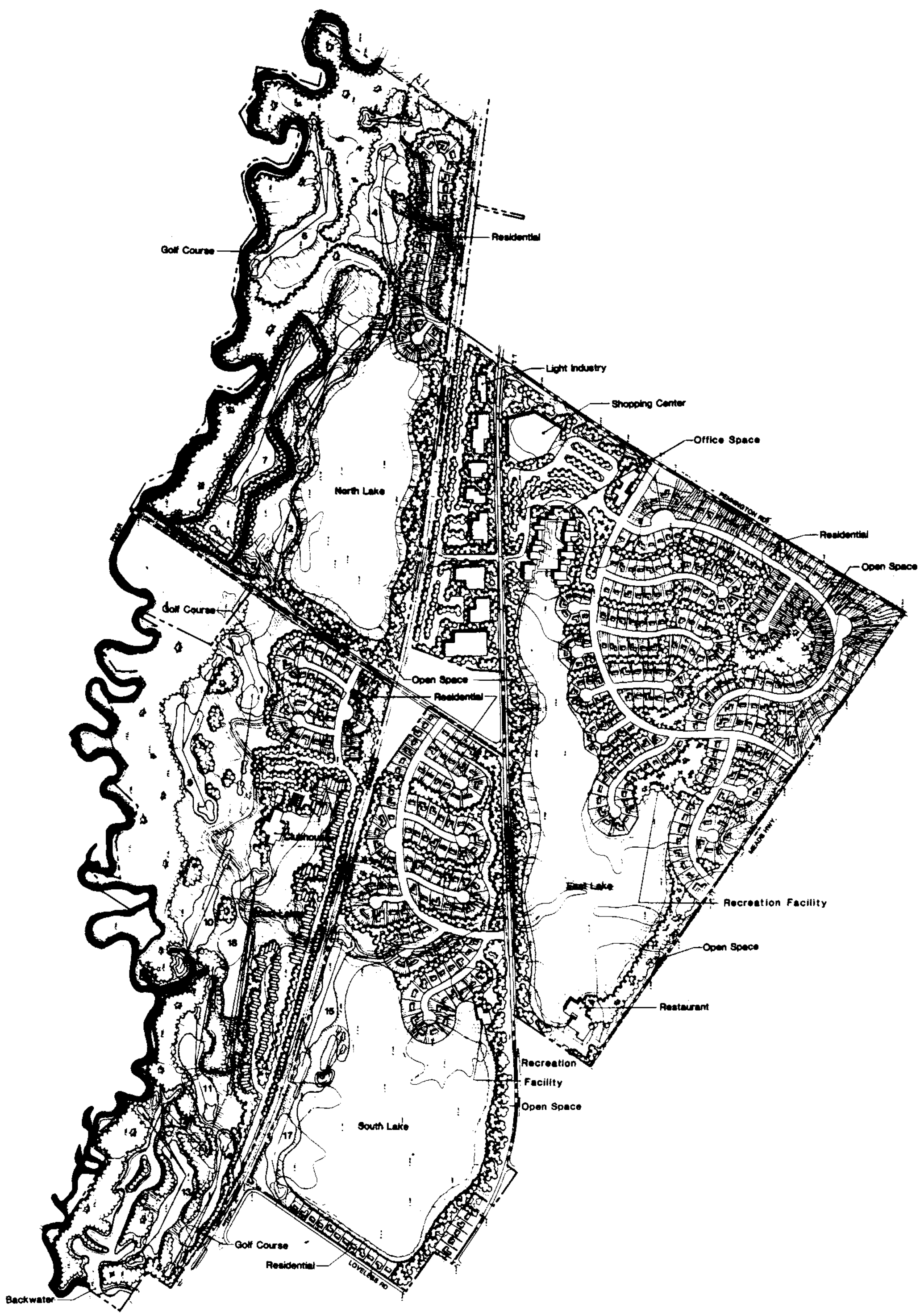


Figure 15. Master site plan.

THE BENEFITS OF MINING REMAIN A WELL KEPT SECRET

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ABSTRACT

During the 1980s, issues involving minerals and the environment were highly publicized. Acid rain, global warming, and the Alaskan oil spill became topics of national attention. Although these issues most directly affected the fuels sector, all indirectly concerned the minerals industry.

In the 1990s, a realization that minerals are a component of the United States' economy will be necessary to balance environmental objectives with mining development. However, before that realization can occur, the importance of minerals and benefits of mining must become better understood by a wider segment of the general public.

INTRODUCTION

As we approach the 21st century in the Year of the Earth and the decade of the environment, the perception of mining is one that is mostly negative.

In the 1980s, the mining of minerals, particularly fuels, but also industrial minerals, was subtly becoming characterized as an obstacle to environmental protection. In the past, specific mining activities were categorized as causing specific environmental problems. In the 1970s, State and Federal legislation, such as the Clean Air and Clean Water Acts, were enacted increasing regulation of the mining industry. The intention of the legislation was for mining to be conducted in an environmentally acceptable manner. In the mid 1980s, with the creation of terms such as "acid rain" and "global warming," environmental protection received much more attention and by more of the general public than during the 1970s. In 1990, it appears as though the question in some quarters has become: How can mining be prohibited or limited?

AREAS AND INFLUENCE

In some ways, its obvious why the general perception of mining is negative. Almost one-half of our Nation's coal is produced in three States with relatively low populations. Kentucky, West Virginia, and Wyoming produced about 480 million tons of the 975 million tons of coal mined in the United States in 1989 (Table 1). These three States have a total population of about 6 million people. In contrast, the six New England States mine no coal and have a combined population of 13 million. Furthermore, fewer people are employed in coal mining; a trend that began in 1981 and has continued since. In that year, about 226,000 miners produced 818 million tons of coal or about 3,600 tons per miner per year. In 1989, about 130,000 miners produced 975 million tons of coal or about 7,500 tons per miner. Thus in the 1980s, coal production increased by 20% while employment declined by more than 40%.

In recent years, severe weather extremes have resulted in brownouts and blackouts (energy shortages) in the South and the Northeast, where very little coal is produced. These blackouts, although rare events, were sufficiently dramatic to affect millions of consumers. However, these consequences were not sufficient to remind these millions of energy consumers that, for the most part, energy or electricity comes from coal, oil, or gas. Similarly, the millions of people living in energy-producing States seem unaware of the source of their energy requirements as well. These people have had enough energy and more or less assume they always will.

Table 1. - Leading Coal Producing States, 1989

	Quantity Million Short Tons	Percent U.S.	Rank
Wyoming..........	168	17	1
Kentucky...........	160	16	2
West Virginia.....	151	15	3
Total...........	479		
U.S. Total....	975		

Unfortunately, most other mineral commodities can also be labeled as "taken for granted." Crushed stone has surpassed coal as the leading mineral produced in the United States with a total output of about 1.2 billion tons annually. In 1989, the United States produced more than 2.1 billion tons of aggregate (sand and gravel and crushed stone). That equates to about 8.5 tons per capita or 325 pounds per person per week for each of our Nation's 248 million people.

MINERAL AWARENESS

How many people know how much and where we get the raw materials—the crushed stone, sand and gravel—to build the structures and highways we need? Most people don't relate the finished products, merchandise they purchase and the roads and highways they drive on to the raw materials utilized to produce these items. Just as most people don't realize coal mining has something to do with turning on a light switch, many people have no idea that mining and the use of industrial minerals is essential to their daily lives.

As we know from Earth Day and the clean air legislation, the United States is placing a high value on the quality of the environment, and the mining industry is faced with environmental regulations that place financial burdens on the industry. In addition to current regulations, there is a great deal of uncertainty concerning regulations now being proposed. This climate of uncertainty makes the planning of new operations or changes in existing operations very difficult. Also, many current operations are paying high prices to clean up environmental problems left from past mining practices, which placed little or no emphasis on environmental considerations. Indications are that the industry will see little relief from environmental regulations and their associated costs for some time into the future; if anything, the trend is toward increased regulation.

The needs of the industry with respect to environmental regulations are threefold: (1) For current and future regulations that are based on sound scientific and engineering data; (2) for the ability to comply with regulations in the most cost-effective manner; and (3) for the development of mining systems that minimize environmental impacts. These three needs seem rather apparent and logical. However, logic is not always one of the criteria used in decisions involving mining. During the past 7 years of economic growth, construction industry demand for industrial minerals has resulted in record outputs of these mineral commodities. Because of urban encroachment into traditional mining areas, opening and expanding industrial mineral operations has become increasingly difficult. Previously, mining was viewed as an activity that created or increased the tax base, employment, and indirect economic benefits for a community. Presently, the general public appears to be becoming more concerned with "quality of life" issues and more reluctant to accept mining development.

LAND USE CONFLICTS

Often times a mine operator presents sound data and complies with environmental regulations and practices, but opposition by the general public results in denial of permission to mine at the local level. Typically, what happens during the course of a land use conflict is that the townspeople rally and form a group to oppose the mine operator. A feeling among group members, similar to nationalism (localism) evolves. The mine operator's sound engineering data, as well as compliance or intention to comply with environmental regulations, becomes irrelevant to the citizens group. Emotion now controls the situation. The mine operator who has "won" permission to mine or expand an operation is now doing so in a town that has been defeated and is hostile towards mining. Thus, the mining company may win the battle, but the industry, as a whole, is losing the war. Although stone and sand and gravel are mined in almost every State, these commodities are low in value compared to coal and, as a consequence, receive little attention.

An example of how mineral resources are sometimes overlooked was examined by the Bureau of Mines at the site of a proposed airport in Denver, CO. New facilities at the airport required an estimated 11 million tons of construction aggregate. During 1986, only 9.8 million short tons of sand and gravel were produced in all of northeastern Colorado, and during 1987, crushed stone production from the same area was only 6.9 million short tons. The area's supply of construction aggregate appears critically inadequate considering the ancillary development in conjunction with the airport.

Permitting of new pits and quarries and for expansion of existing operations is presently at a standstill in the greater Denver metropolitan area because of adverse public reaction to the aesthetics of these operations. Because planning boards in Colorado have been reluctant to approve even small operations, aggregate for the airport construction may have to be transported from distant sources. Such transportation would increase the cost of the aggregate and, thereby, the costs of airport construction. It is possible that the large quantity of aggregate required would limit the supply of the area's aggregate producers to other consumers during the period of airport construction.

Another example of a problem in supply and demand of construction aggregate is emerging in Ohio. A major issue for that State's aggregate industry is the availability of land to mine.

A number of aggregate deposits in Akron, Canton, Cincinnati, Columbus, and Dayton, along with other areas, were used for building purposes or were closed to mining by zoning. These highly populated cities are the same areas in which demand for construction aggregate is the greatest. Again, because aggregate is a bulk commodity, haul distance is typically a major component of the price. According to the Ohio Aggregates Association, the cost of mineral aggregate produced in southern Columbus doubles by the time it is delivered to northern Columbus.

In addition, tax revenues were used to purchase more than one-half of all the aggregate sold in Ohio. State, county, township, and municipal governments indirectly purchased large quantities of aggregate through contract construction for road maintenance and building projects. Federal funding was usually included in public works programs involving airports, dams, locks, erosion control, and waste-treatment facilities. Thus, indiscriminate zoning or land-use decisions that eliminate the possibility of developing an aggregate deposit can ultimately result in higher taxes to fund public works and construction projects.

EAST VERSUS WEST

Land use conflicts involving industrial minerals, particularly stone and sand and gravel, are expected to continue especially in the Eastern United States. The 26 Eastern States, as shown in Table 2, account for about 60% of the Nation's production of stone and sand and gravel and 60% of the population, but only 24% of the total area. About 1,435 short tons of aggregate is mined per square mile in the eastern part of the United States compared with only 308 tons in the West.

Table 2. - Production, by state, Eastern United States

State	Production[1] Million Short Tons	Short Tons Per Capita	Short Tons Per Square Mile
Alabama	41.3	10.1	799
Connecticut	18.4	5.8	3,680
Delaware	1.9	2.7	950
Florida	100.9	7.8	1,719
Georgia	56.2	8.8	954
Illinois	95.7	8.2	1,700
Indiana	66.0	11.8	1,822
Kentucky	53.6	14.5	1,327
Maine	9.9	8.3	297
Maryland	51.9	11.0	4,943
Massachusetts	27.4	4.6	3,301
Michigan	90.0	9.7	1,538
Mississippi	15.9	6.1	333
New Hampshire	10.6	9.6	1,140
New Jersey	32.4	4.2	4,154
New York	74.8	4.2	1,523
North Carolina	60.8	9.2	1,154
Ohio	94.1	8.6	2,278
Pennsylvania	115.1	9.6	2,541
Rhode Island	2.2	2.2	1,833
South Carolina	28.2	8.1	907
Tennessee	60.4	12.3	1,435
Vermont	7.0	11.7	729
Virginia	78.8	12.9	1,931
West Virginia	13.3	7.0	550
Wisconsin	53.3	10.9	948
Total or average:			
East	1,260.1	8.3	1,435
West	844.0	8.7	308
United States	2,104.1	8.5	581

[1] Combined production of crushed stone and sand and gravel preliminary 1989 data.

The leading State in tons of aggregate produced per square mile is Maryland. Since 1982, output of aggregate has more than doubled from 24.8 million tons to 51.9 million tons in 1989.

This unprecedented demand for aggregate in Maryland reflected an expanding economy and growing population. New roads, homes, and commercial buildings were needed, and mineral aggregate was an essential raw material used in this construction. However, the pronounced increase in construction and mining activity resulted in opposition to mineral development, particularly in areas where mining occurred or was proposed. In 1988, opposition by residents to the opening or expansion of quarries in Carrol County was the impetus for introduction of House Bill 407 in the Maryland General Assembly. That measure would have assumed a quarry operator to be liable for damages to properties within a 3-mile radius of the quarry. The bill was defeated in committee, but similar legislation has been proposed in each of the last two sessions. Failing at the State level, one county has adopted revised zoning ordinances requiring extensive environmental impact studies before land can be zoned for use as a quarry. Balancing environmental considerations and natural resources development in land-use planning has become increasingly difficult in Maryland; and, in many cases, the decision has been finalized only through the courts.

SUMMARY

A few years ago, I asked a number of mining industry officials what should be done to keep mining viable in the 1990s. Many of the responses were what everyone is trying to do, such as improve technology so as to remain productive and competitive. Others were to make local and State government officials more aware of the need and uses of minerals in conjunction with land use planning and decisions. Another response was that people working in the mining industry should spend less time talking to each other and more time talking to people who are not familiar with the importance of minerals. For mineral development interests to be balanced with environmental protection, a better understanding of mining will be needed in the 1990s.

CREATING A GOOD IMAGE

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At Luck Stone Corporation we have a motto "We Care". The motto reflects the attitude of the company towards its employees, its plant operations and stone centers, its customers, its neighbors and the communities in which it operates.

As you know, "We Care", "Commitment of Excellence" and other similar phrases are used liberally by many companies. Luck Stone Corporation, however, does not only believe in such ideals, it preaches them and most of all practices them. It is through this commitment to caring for our employees, plant operations and stone centers, customers, neighbors and communities that Luck Stone has enjoyed the success that it has.

EMPLOYEES

First, we care for our employees. Every company can say "People are Our Most Valuable Asset", but do they treat them that way? If employees are treated fairly they respond in a very positive manner. They respond by announcing to their friends, neighbors and the community what a good company they work for. This goes a long way in how a company is perceived by individuals on the outside. You can imagine what happens when you have disgruntled employees talking bad about the company.

How do we create this good will that is carried forward out into the community?

1. We involve our employees - they are given opportunities for input. Their supervisors and managers are available to discuss their thoughts, suggestions and problems. Our President personally visits with each employee at his or her job location.

2. We give them training and reimburse them for job related courses that are taken.

3. The production employees are challenged and rewarded by a "Productivity Improvement Program."

4. Employees are recognized for doing well:
   - Safety banquets
   - Service pins
   - Family picnics
   - Outings
   - Newsletter
   - Benefits such as Medical, Pension Plan

5. Profit sharing.

6. Mission Statement: What the employee can expect from the company and what the company expects from the employee.

We are fortunate enough to have maintained a nonunion environment where employees have individual rights and can strive for improvement and are personally recognized for their performance. Even though individuals are recognized, a team work concept is utilized throughout - we all depend on one another in order to accomplish a clear cut mission. We all have to have a mission or target. When we meet these goals we have earned our success and therefore can take pride in ourselves and in our company.

PRODUCTION

The work place is one of good equipment and facilities. We replace old equipment, and build new, with the latest and most up-to-date equipment possible. Most of these improvements offer improved productivity but a lot of them make a safer and cleaner work environment. Also they make us a better neighbor.

1. Dust controls - such as collectors and high pressure water trucks.

2. Noise reduction efforts, jaw crusher in the hole.

3. Stockpiling by conveyor vs. trucks.

We have our own SOP for blasting; more stringent than most standards for the communities where we are in business.

We have been able to increase production without added overtime by automating parts of our plants. Not only is there more stone produced but this method saves on electrical power by leveling out power demands, reduces amount of overtime, which also saves on wear and tear of our employees.

We provide our plants with good equipment and facilities and we expect it to be taken care of. Good housekeeping and beautification go hand-in-hand with good production. Pride in what they have to work with causes employees to do a better job and to have pride in themselves and their company.

CUSTOMER

This is where it takes a special effort by everyone within the company. Successful companies do not rely on their sales force to be the only sales-oriented people within the organization. That customer is the one who ultimately pays the bills. We constantly have to gain his respect and give him the service he needs.

Of course, we have our sales force in the field making calls on customers, but as one of our salesmen used to say he could sell anyone the first load of stone but it would be the plant personnel who would keep him as a customer. The office manager has to receive his call and order with courtesy and professionalism, the loader operator has to load his truck expediently and carefully, and the product had to be produced to the required specifications and the office manager must weigh them out in an efficient but quick manner. So the salesman is right, it takes a lot of effort at the plant to service and keep the customer.

Other things we do in our sales effort:

1. Work closely with customers to determine their specific requirements and schedule timely deliveries.

2. All orders, both large and small, are important to us and receive the same prompt courteous attention.

3. Truckers are constantly reminded of their effect on customers and the community. Maintain a firm stand on legal weight limits and required tarps. Hold courtesy meetings.

4. Work to achieve good communications between all departments to guarantee customer satisfaction.

5. See that our office managers and plant managers get to know our customers on a personal basis.

6. Customers are invited to tour our plants and meet the people who produce our products.

7. Have promotional items to give to our customers - hats, pens, pencils and other things.

8. Use pamphlets and brochures that are available from the Virginia Aggregates Association, National Stone Association for distribution to interested customers. An example is the erosion control brochure which is in constant demand.

9. Display "Thank You" signs.

A lot of what we do to care for the customer comes as a result of surveying our employees - at all levels - to see how we could service our customer best. Many of the suggestions are being used. Ideas come from many unexpected places, the thank you sign is an example.

Not only does a satisfied customer offer more sales, but they too are members of a local community and if they speak well of your company, it enhances your image.

NEIGHBORS

As much goes into the consideration of neighbors in selecting a new site as anything. How can we operate here and get along with property owners that surround us? We also give the same consideration to those who live near our existing operations.

Earthen berms have been one way in which we have lessened the effect of our activities. They block the view of the operation, they muffle the sound and they can be planted and shaped to enhance the landscape.

We set out a seismograph, sometimes two, on every blast. This not only gives a permanent record of the blast but it gives exposures to the neighbors that we care enough about them to put out the seismograph. It gives one an opportunity to talk to a complainant and have something positive to talk about.

Along these lines, our plant managers and area managers periodically visit our neighbors. Certain ones at times are visited by officers of the company. This personal contact goes a long way.

We have removed snow from driveways and in subdivisions where the roads are not in the state system. In a very unsystematic way we give stone to our neighbors. Free use of equipment for such purposes as welding and weighing of grain is allowed. We draw the line if we feel we are being abused by our willingness to assist.

We beautify our entrances and maintain them neat and clean. Maintaining the entrance is just as important, or even more important, than beautifying. This is what reminds the neighbors the most of what the quarry is about. So put on your best face, and then see that it is carried inside to the plant and pit area, not just a facade.

We are most proud of our "About Face Awards" for beautification and improvements to the environment and working conditions at our plants. If you are not involved in making improvements towards a goal of entering a similar program - do so. You will find the results very rewarding.

We were before a local board for rezoning and one of the supervisors stated he had read where we had won a national award for beautification and he was impressed that we had gone to such efforts. Programs that have been recognized as strong and credible offer a great deal to those who enter and win.

Two unsolicited awards received at Luck were from the "Virginia Society of Landscape Architects" (as caretakers of the land) and the local City and County Council of Garden Clubs (for beautification at our entrance and along the road). Most of this is not so much what we did in the way of landscaping or spending big dollars, it was just maintaining the grounds, as we call it, good housekeeping.

The impression you make on your neighbors or what they can see is the image they will have in their minds of the whole operation.

COMMUNITY

Your neighbors are, to you, a very important part of the community where you do business, but let's look at the broader picture - your local community. You must have its support to run your business.

We get involved by:

1. Donations & contributions, primarily:
   a. Fire-Rescue Squad

b. Youth organizations
2. Talents of employees are used within the area to:
 a. Speak to groups and organizations
 b. Serve on boards and commissions

3. Volunteers

4. Participate in local celebrations or parades

5. Exhibit at community fairs or trade shows

6. We give group tours

7. Hold open houses

8. Contact of local officials

9. We offer our facilities to groups for meetings

10. Our road equipment that travels through the communities is kept neat and clean.

Things in our industry can be changed and we must all strive to change and make our industry more readily accepted by the public. Our forefathers did not leave us with an easy task, but let us take the initiative to make conducting business in the minerals industry an easier task for those that may follow us.

I hope you have gained some ideas about improving the minerals industry's image and how to get more exposure for the good things that are being done in the industry. But most of all, this will not do us any good, unless we go back to our individual locations and emphasize to others how important good public relations is to the minerals industry and to each of our jobs. You have to make it happen. And believe me, the benefits of a good image will pay dividends in many ways.

IMPORTING CONSTRUCTION AGGREGATES TO THE CONTINENTAL UNITED STATES

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ABSTRACT

In recent years, there has been increasing interest to develop and promote aggregate imports to the United States. Unlike cement, which has been imported for decades, importing of road aggregate by domestic and foreign producers has been increasing along the eastern, southeastern, and Gulf of Mexico ports. Currently, other producers have either explored or delineated areas of potential deposits for crushed stone which can be mined and shipped economically to the United States.

This interest is sparked by environmental concerns in opening new deposits in the United States. However, the importers of aggregates must also be concerned with varying aggregate specifications among the states. This paper will outline and discuss these concerns and will also discuss some factors regarding the production of construction aggregates, such as geology, market economics and transportation.

INTRODUCTION

Crushed stone and sand and gravel for use in road base, portland cement concrete and bituminous concrete mixtures is an important commodity in the United States. In 1989 the total crushed stone sold in the U.S., according to the U.S. Bureau of Mines, was estimated at 1,220,000,000 short tons. Sand and gravel use for the same end products accounted for an estimated 888,000,000 short tons in the same year (U.S. Bureau of Mines, 1990). Tonnages such as these have increased activity to explore and open new deposits throughout the United States. However, it has also become increasingly more difficult to permit a quarry site in urban areas where the aggregate is needed.

The complexity of permitting new deposits in the U.S. is costly and time-consuming. This factor, along with others, has helped foster some companies, both foreign and domestic, to explore and develop deposits in Nova Scotia, Newfoundland, Bahamas, Dominican Republic, Mexico, and Jamaica to produce and ship aggregate to the United States.

Shipping bulk commodities by vessels on major waterways is not new as cement has been shipped from foreign ports to the United States and construction aggregates have moved via river courses to their destination for decades. Generally, water transportation is less expensive per ton mile than rail or truck.

Perhaps the importing of construction aggregate on a large-scale movement was Foster Yeoman's 1985 shipment of granitic rock from Glensanda, Scotland to Houston, Texas. Since then, major aggregate companies have strategically located potential quality stone for import purposes. Sand and gravel imports increased from 123,000 tons in 1983 to 250,000 tons in 1988 (U.S. Bureau of Mines, 1988-1989).

The importing of construction aggregates to the United States is controlled by many factors: environmental, specifications, geology, production, and transportation costs (economics).

ENVIRONMENTAL

One of the foremost factors which may play an important role for domestic producers to seek rock sources in other countries is environmental permitting. Like other mining industries, crushed stone and sand and gravel must comply with various state, local, and federal regulations before the site can be mined. The process is sometimes time-consuming and expensive procedure in most populous areas.

Pre-emption of aggregate deposits by local zoning laws is becoming a key issue in their development. Proximity to the consumer is vital to the aggregate producer. To minimize transportation costs, quarry sites need to be located close to the population centers. Transportation costs can increase the delivered price of the aggregate by over 100 percent of the f.o.b. price. Implementation of land-use regulations is increasing throughout the United States. This tends to displace aggregate production further away from its market.

Urban growth (which creates much of the construction aggregate market) has often expanded over once-potential resources, mainly with sand and gravel deposits. A prime example of urban encroachment was the focus of recent studies by the Maryland Geological Survey. Within Anne Arundel County, a suburban area near Baltimore and Washington, D.C., the effects of zoning, exhausted aggregate resources, and urban encroachment were studied. In 1940, nearly 70 percent of the original sand and gravel resources were available to production. As of 1980, this percentage had dropped to less than 20 percent (Langer, 1988). In addition, two proposed quarry sites were denied zoning change in the Frederick Valley and one in Montgomery County in the State of Maryland. In Georgia, it was reported that Vulcan Materials Company has had a difficult time rezoning a proposed site north of Atlanta. Conversely, it seems that foreign governments such as Canada, Bahamas and Mexico promote new mining opportunities.

The monies from foreign investors, especially the United States, have helped improve some local economies of these areas and, in some places, employment by these operations are extremely welcome.

SPECIFICATIONS

Specifications have a great influence on mineral reserves and, therefore, imports of construction aggregates to the United States. Specifications for aggregate used in construction are usually established by the individual states. These specifications generally follow guidelines and testing procedures that have been established by the American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO). Certain government agencies have also established their own specifications for construction materials (e.g. U.S. Army Corps of Engineers, Federal Aviation Administration, etc.). Aggregate specifications are based on the inherent chemical and physical properties of the material and the resultant physical properties after processing. Product line for aggregate markets are defined by the parameters established by testing. Some of these properties are discussed below.

GRADATION

Gradation is the size distribution of particles in an aggregate. The gradation of aggregate in concrete affects the amount of other constituents required in the concrete mix.

PARTICLE SHAPE

The shape of the individual particles within an aggregate can affect the workability of the concrete aggregate. An increase in the percentage of flat or elongated particles will generally require an increase in the amount of sand required for the concrete. This, in turn, increases the water and cement requirements. A maximum tolerance level for the percentage of flat and elongated particles is generally set by the states.

SOUNDNESS

The soundness test is an attempt to quantify the ability of an aggregate to withstand weathering. Resistance to freeze-thaw and wetting-drying cycles is also important. Freeze-thaw tests, along with sodium or magnesium sulfate soundness tests, characterize the weathering resistance for the concrete and bituminous mixes.

HARDNESS AND STRENGTH

The hardness and strength of an aggregate characterizes its ability to resist mechanical breakdown. This is usually determined by the Los Angeles Abrasion Test. The states usually dictate the maximum percent loss by weight of the aggregate after testing.

SKID RESISTANCE

The surface course of concrete or bituminous mixtures in road construction requires aggregate that has a high friction resistance. High friction aggregate generally possesses a high resistance to surface polishing. This results in a top course that is resistant to skidding. These materials usually contain siliceous components.

The characteristics described above are used to distinguish in which market sections a given aggregate can be sold and represent only the basic requirements for coarse aggregate. An importer must be aware of each state's specifications for aggregate material.

For example, in the State of Georgia, the specification for Los Angeles Abrasion, B grading is 60% loss. This parameter should be met easily by most importers. However, it was written to accommodate the rock in the general area of Atlanta. South Carolina also has that same percentage loss as their specification. Conversely, Massachusetts specifications on Los Angeles Abrasion are 30% for bituminous concrete mixtures, 42% for portland cement concrete, 45% for subbase and 50% (an ASTM specification) for all other products. The contrast can cause the same imported material to be accepted in one state and not another.

New York State has seemingly the strictest specifications for quality control of their construction materials. Besides a 10-cycle magnesium sulfate test on coarse aggregate with an 18% loss, Los Angeles Abrasion limits calls for a 35% loss, for crystalline, 45% loss. The NYSDOT Bureau of Materials also requires a geologic report and drill hole coverage. Therefore, a quarry in the Bahamas, shipping material to New York for State projects, must have core holes, testing, inspection by an outside geologist and a geologic report. Furthermore, the geologists from the NYSDOT Bureau of Materials will need to visit the site.

The following table shows the different Los Angeles Abrasion and soundness specifications among some eastern and gulf coast state:

	Soundness			L.A. Abrasion	
State	Cycles	Max. Salt	Loss %	Portland Cement Concrete	Bituminous Concrete
TX	5	$MgSO_4$	18	40	45
		$NaSO_4$	12		
LA	5	$MgSO_4$	15	40	40
MS	5	$MgSO_4$	12	40	45
AL	5	$NaSO_4$	10	50	48
FL	5	$NaSO_4$	12	45	45
GA	5	$MgSO_4$	15	60	60
SC	5	$NaSO_4$	15	60	60
NC	5	$NaSO_4$	15	55	
VA	5	$MgSO_4$	12	40	
MD	5	$NaSO_4$	12	50	
PA	5	$NaSO_4$	10		
NY	10	$MgSO_4$	18	35	
MA	5	$NaSO_4$	10	42	30

GEOLOGY

Geology is one of the most critical controls on the production of construction aggregates. Suitable source material must be present to produce aggregate of proper quality to meet the specifications. The occurrence of both sand and gravel and crushed stone deposits are dependent on geologic processes which in turn, control the suitability of the material throughout the deposit.

Most of the deep water ports on the eastern seaboard and Gulf States are located in the Atlantic and Gulf Coastal Plains. The general geology in these areas are unconsolidated sand, gravel and marl. Where the rock outcrops are near the coast, it is generally semi-lithified carbonates, soft and sometimes unusable for aggregate. Therefore, aggregate must be shipped by rail or truck, sometimes barge, from the interior of these states where rock is hard and competent. At the northeastern ports, such as Newark and Boston, rock is close to these densely populated areas. However, quarry operators must ship the stone into the city from perhaps 40 miles or more, contending with the city traffic, thus increasing the cost of the stone delivered.

These two cases add a positive note to the importers by helping them be competitive. For example, a producer of bituminous concrete located in the panhandle of Florida buys his coarse aggregate from a Kentucky producer who transports the aggregate by barge down the river system to the intercoastal waterway until its destination is reached. This producer reportedly buys this stone for less cost than railing the material from Montgomery, Alabama which is actually less distance to his plant facility.

Houston, Texas must bring durable aggregate from San Antonio because of the geology around the area. When stone must be railed or trucked in from great distances, the importer becomes competitive.

MARKETS

The success of a construction aggregate operation is dependent upon its market share, size, and growth. Major metropolitan areas provide a good base market for aggregate operations. Market share for a given operation is dependent on such factors as geologic reserves, plant capacity, plant location, and the general business philosophies of the management. A good quality crushed stone from other countries may be competitive against the domestic producers, especially in the Eastern and Gulf States.

Already aggregate has been shipped great distances from its source to some port cities. Areas such as Portland, Maine; Boston, Massachusetts; Philadelphia, Pennsylvania; Baltimore, Maryland; Norfolk, Virginia; Charleston, South Carolina; Brunswick and Savannah, Georgia; Jacksonville and Tampa, Florida; Mobile, Alabama; New Orleans, Louisiana; and Houston, Texas are all potential markets of quality crushed stone. These ports have the capabilities to accommodate large cargo vessels and have the facilities to unload and distribute the material to the interior cities. New York City, Newark, New Jersey, and New Haven, Connecticut harbors are less attractive for imports not only because the port facilities are inadequate, but because quality stone exists nearby. Last year Lone Star reportedly shipped approximately 30,000 tons of aggregate by vessel from their Nova Scotia operation via the Hudson River to Clinton Point, New York for distribution.

ECONOMICS

PROCESSING

Costs in producing crushed stone or sand and gravel generally average $2.97 and $2.60 per ton, respectively, throughout the United States (Robertson, 1989). In the proximity of Atlanta, Georgia an independent survey in early 1988 revealed the following costs:

TYPICAL COSTS
Crushed Stone

Function	Cost/Ton
Drill and Blast	$0.29
Pit Excavation	0.63
Loading and Hauling	0.32
Processing	1.32
Stockpiling	0.18
Stripping	0.15
Supervision	0.25
Maintenance	0.36
Administrative	0.16
Miscellaneous	0.19
TOTAL COST	$3.85

The above costs may be high, but give an overall picture. The following table shows cost in dollars of coarse aggregate in some port and interior cities. When analyzing both tables, economics play an important role in importing aggregates to the United States.

COST OF SAND AND GRAVEL AND CRUSHED STONE IN VARIOUS URBAN AREAS OF THE UNITED STATES

	Gravel		Concrete Sand	Crushed Stone	
City	1"-3/4"	3/4"-3/8"		Concrete Coarse	Asphalt Coarse
Atlanta	6.30	7.80	10.50	6.30	8.25
Baltimore	15.00	9.25	8.25	6.85	9.05
Birmingham	11.20	11.20	11.20	4.50	4.50
Boston	11.00	11.00	9.50	13.50	14.50
Chicago	5.00	5.00	5.00	7.00	8.00
Cincinnati	6.20	6.20	5.20	9.20	9.20
Cleveland	7.00	7.00	3.00	7.00	7.00
Dallas	6.60	6.60	5.60	4.10	4.00
Denver	8.50	8.25	5.20	7.70	8.40
Detroit	13.00	13.00	5.75	5.10	7.44
Kansas City	15.50	10.75	3.00	6.50	5.25
Los Angeles	8.20	8.25	8.35	6.73	5.75
Minneapolis	7.00	7.00	3.45	7.00	5.75
New Orleans	8.25	8.10	5.50	11.15	11.15
New York	12.30	12.30	10.42	8.40	9.15
Philadelphia	9.80	9.80	7.60	7.75	8.75
Pittsburgh	9.70	9.70	8.40	6.55	7.30
St. Louis	9.50	9.00	9.00	4.60	5.10
San Francisco	8.40	8.37	8.50	6.75	5.74
Seattle	5.00	5.00	4.50	5.35	5.35

*Cost in dollars per short ton, f.o.b. plant or distribution yard. (Source: Engineering New Record, April 5, 1990.)

TRANSPORTATION

Three major modes of aggregate transportation in the United States are truck, rail, and water. Baseline costs for these types of transportation are generalized below:

Truck - $0.07 to 0.25/ton-mile; $0.10 average
Rail - $0.02 to 0.08/ton-mile; $0.05 average
Water - Less than $0.01 to 0.05/ton-mile; $0.03 average

These baseline costs do not include factors, such as reloading, lock and port fees, and demurrage. These added expenses can have a major effect on the delivered price of the aggregate. Due to increasing urban congestion, there has been a trend to a ton-hour rate for aggregate distribution in urban areas. Local conditions also control the transportation methods and costs for construction aggregates. Truck transportation has historically dominated the movement of aggregate from plants to their markets. Truck transport provides flexibility in meeting shifting market areas. In cases where rail or water transport is used, the aggregate is shipped from distribution yards to the final consumer by truck.

As a direct result of the distancing of producers from their market by urbanization, rail transport of aggregate to distribution yards has been increasing. Deregulation and its reduction in freight rates has also contributed to this. Unit trains of 50 to 100 rail cars (usually 90 tons per car) ship aggregate into metropolitan areas such as Denver, Colorado. In other cases, a lack of local material that can meet specifications has generated transportation of aggregate by rail. In Virginia, crushed granitic rock is railed from Emporia, Virginia to the Suffolk-Norfolk metropolitan area along the Atlantic Coastal Plain. The lack of coarse aggregate material along the coast justifies this 60-miles rail haul.

Water transport of aggregates also occurs in select regions of the United States. Lack of adequate source material proximal to an urban area can encourage suppliers to barge aggregates in from another area. Skid resistance aggregate is commonly shipped from Maryland to Atlantic coast cities where such material is needed.

How transportation affects the import competitiveness was approached by Timmons and Harben (1987). His example follows:

> To reach a Gulf Coast market, aggregate from inland sources incurs $4.00 per ton in freight costs (by rail). With the average f.o.b. plant price of $8.86 per ton, this brings the total price to $12.86 f.o.b. at the Gulf Coast distribution yard. For Scottish granite, the total price was $10.70 to $11.15 per ton f.o.b. at the Gulf Coast terminal. In both cases, the cost for distribution to the final customer would be added.

SITES AND COMPANIES

Excluding those companies shipping material across local international boundaries, the following list of companies indicates expanding interest of imports to the United States via oceanic shipping.

o Foster Yeoman Limited, Glensanda Quarry, Scotland has shipped granitic crushed stone to Houston, Texas starting in 1985.

o Lone Star Industries, Auld Cove, Nova Scotia, shipped granitic rock to Charleston, South Carolina, New York State and other eastern seaboard cities.

o Dravo Basic Materials Company, Freeport, Grand Bahamas began in 1989 shipping limestone to Mobile, Alabama and Tampa, Florida.

o Vulcan Materials Company is developing a limestone quarry in the Yucatan peninsula of Mexico. Shipments may begin in late 1990 or 1991 to Houston, Texas and other Gulf States.

o The Newfoundland Resources & Mining Co. Ltd., owned by Explaura Holdings PLC, has recently (October 1989) taken their first shot (blast) and may begin shipping limestone to the eastern states. The quarry is located on the Port au Port Peninsula.

o Marcona Oceanic Minerals, Ltd. has been producing limestone and aragonite from its operation at Sandy Cay south of the Bahama Islands. Their production mainly is used in the glass industry; however, some shipments were made for construction purposes.

o Ideal Basics has been producing chemical grade limestone in the Dominican Republic and shipping it along the east coast. Reports have indicated their interest in producing construction aggregate for import purposes.

o Riverside Construction Materials have interest in a site in Nova Scotia, 95 miles north of Yarmouth.

o Other sites which have been explored include one in the Southeastern Dominican Republic near the Haitian border by Vulcan Materials in 1986 before they settled on Yucatan Peninsula. According to the January, 1989 Rock Products Magazine, Dravo Basic Materials Company is exploring possible sites in Mexico. Reports have indicated that two companies have expressed interest in exploring the Baja of Mexico for aggregate with thoughts of shipping the material by vessel into Los Angeles, California.

In Newfoundland, near Long Harbour, a group of entrepreneurs are developing interest in that site. The wharf and loading facility are in place from previous owners who imported phosphate from Florida for their manufacturing process. The facility has shipped slag as a by-product from their process to Jacksonville, Florida for use by Dravo in some of their construction projects.

Major companies are exploring other sites in Mexico, Caribbean Islands and Ireland. In January 1989, a newsletter published by the Geological Survey of Ireland stated that several companies are examining the Ireland coast as a source of aggregate for the eastern United States.

SUMMARY

This paper has briefly explored some of the factors which determine whether an importer of aggregates to the United States can be competitive. It was determined that among the five factors discussed, all have influenced in some manner both the importer and those wishing to become importers of aggregate to the United States.

o Environmental and zoning concerns have made it difficult to open new quarry sites in populous areas in the United States where construction aggregate is needed.

o Increased transportation costs related to higher unit costs per mile, longer distances and newer truck weight laws have increased delivered costs.

o Specifications which are different in every state can cause some stone to be accepted in our State and not another.

o Costs of producing the product as related to energy and labor may be less expensive in countries outside the United States; however, production costs for crushed stone remain essentially the same throughout the United States and other countries.

Although imports of crushed stone and sand and gravel increased since 1987, only 0.5 percent is consumed by the United States. Industry leaders seem very cautious when asked the future impacts of imported aggregate to the United States. The interest and development of these sites takes careful planning and cost accounting.

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SANDSTONE AGGREGATE RESOURCES IN SCOTT COUNTY, VIRGINIA

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ABSTRACT

Scott County, Virginia has abundant sandstone and quartzite resources. The Virginia Division of Mineral Resources is conducting an ongoing program to evaluate high-silica and related mineral resources in Virginia. As part of this program, the major sandstone-quartzite units in Scott County were examined to identify potential sources of non-polishing aggregate for use in asphalt surface courses.

Eight sandstone units in the Valley and Ridge and Appalachian Plateaus provinces of southwestern Virginia were examined and sampled for testing. These include: the Clinch Sandstone (Silurian), Wildcat Valley Sandstone (Devonian), Fido Sandstone (Mississippian), undivided sandstone units in the Pennington Formation (Mississippian), Stony Gap and Tallery Sandstone Members of the Hinton Formation (Mississippian), and lower and upper quartzarenite units of the Middlesboro Member of the Lee Formation (Pennsylvanian). Composition of these units range from quartzarenite and quartz-pebble conglomerate to calcarenaceous sandstone.

Non-polishing aggregate used in an asphalt surface course must meet specific engineering and physical properties requirements to resist skidding, traffic abrasion, and the disintegrating effects of weathering. Field and laboratory data indicate the quality of aggregate varies between the formations and within each sandstone unit. This may be due to local geologic structure and rock composition. Los Angeles abrasion and soundness test data indicate that selected sandstone samples meet the requirements and qualify for use as coarse aggregate in asphalt surface courses. Rocks with the greatest potential to be a source of non-polishing aggregate are the Fido Sandstone and Pennington Formation in the Valley and Ridge province, and the tightly folded and overturned parts of the Hinton and Lee Formations found along the southeast flank of the Pine Mountain thrust fault block.

INTRODUCTION

To evaluate potential sources of non-polishing aggregate, twenty-five (25) samples were collected and analyzed from the eight major sandstone units found in Scott County, Virginia, which is located in the Valley and Ridge and Appalachian Plateaus provinces (Figure 1). These sandstone units include: the Clinch Sandstone (Silurian), Wildcat Valley Sandstone (Devonian), Fido Sandstone (Mississippian), undivided sandstone units in the Pennington Formation (Mississippian), Stony Gap and Tallery Sandstone Members of the Hinton Formation (Mississippian), and lower and upper quartzarenite units of the Middlesboro Member of the Lee Formation (Pennsylvanian) (Figure 2). Field and laboratory data show that eight selected samples from the Fido Sandstone, and Pennington, Hinton, and Lee Formations meet the requirements for non-polishing aggregate used in an asphalt surface course; while test results for other samples identified only poor to marginal quality aggregate. This indicates additional commercial sources of non-polishing aggregate may be developed in southwestern Virginia.

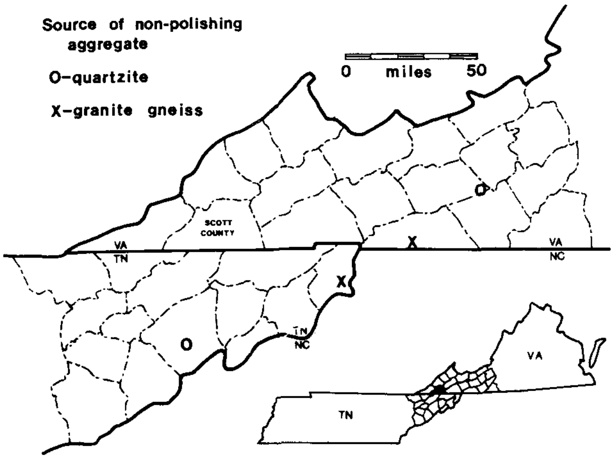

Figure 1. Location map of Scott County, Virginia.

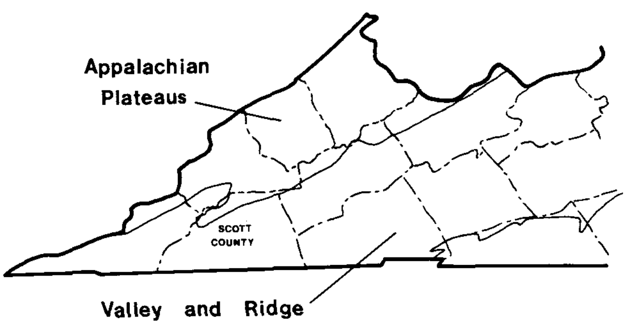

Figure 2. Geologic map of the principal sandstone formations and sandstone aggregate sample locations in Scott County, Virginia.

The Virginia Division of Mineral Resources (VDMR) has conducted research on potential sandstone high-silica resources for many years. Recent reports in Virginia include studies in Clarke, Frederick, Page, Rockingham, Shenandoah, and Warren Counties (Harris, 1972); Augusta, Bath, Highland, and Rockbridge Counties (Sweet, 1981); Alleghany, Botetourt, Craig, and Roanoke Counties (Sweet and Wilkes, 1986), and an overview of silica resources in Virginia (Sweet, 1986).

Industrial sandstone, high-silica sand and sandstone aggregate have been produced from the Valley and Ridge, Appalachian Plateaus, and Coastal Plain provinces in Virginia. Development of additional sandstone resources include potential use as aggregate for construction and road building, and specialty sands used in glass manufacture, filter sand, hydraulic fracturing, and abrasives.

Engineering specifications define very strict physical property requirements for aggregate used in road construction. Historically, the only sources of crushed stone used as non-polishing aggregate in southwestern Virginia have been quartzite from the Erwin Formation (Cambrian) and granite gneiss from the Cranberry Gneiss in the Elk Park plutonic group (Precambrian). Both quartzite and granite gneiss are actively quarried in Virginia and Tennessee (Figure 3). Crushed stone from these quarries must be imported into much of southwestern Virginia because local sources of non-polishing aggregate are not presently available. This often results in long transportation distances and increased aggregate costs. Additional local sources of non-polishing aggregate could reduce the transportation distances in much of the region and may lower the cost of delivered aggregate.

There are no metamorphic rocks similar to the Erwin Formation or Cranberry Gneiss found in Scott County; however, the region contains sandstone resources which are a potential source of non-polishing aggregate. It has long been assumed that sandstone units found in the Valley and Ridge and Appalachian Plateaus provinces of this region did not meet the physical property requirements for use as non-polishing aggregate in road construction; although no published data have been found to support this conclusion. This report provides field and laboratory data to assist in the evaluation of the sandstone units found in Scott County as potential sources of non-polishing aggregate.

Field data and laboratory test results indicate that the composition of the sandstone unit and the quality of aggregate varies greatly between the different sandstone formations, and within each formation or member. Silurian and Devonian sandstones in the Valley and Ridge province tend to be more friable and less resistant than Mississippian and Pennsylvanian sandstones in the Valley and Ridge and Appalachian Plateaus provinces. Furthermore, samples collected from the folded and faulted southeast flank of the Pine Mountain fault block were comparatively harder and more resistant than flat-lying rocks from the same formation. This indicates that local geologic structures, which subjected the sandstone to additional stresses and compression, may have enhanced the physical properties of hardness and resistance. In addition to local and regional geologic structures, other factors such as rock composition, grain size, and grain bonding characteristics influence the quality of sandstone aggregate. Petrographic properties and their relation to abrasion are discussed by Koning and Cavaroc (1989).

ACKNOWLEDGMENTS

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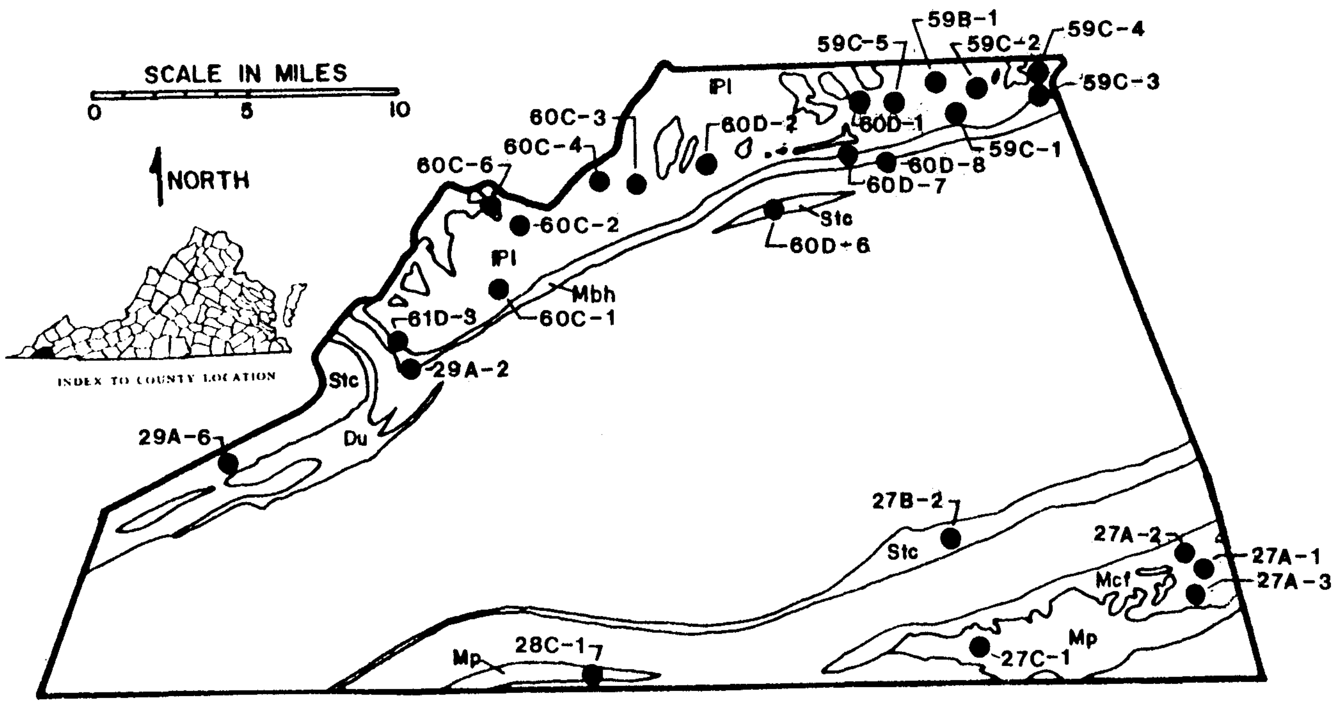
SANDSTONE AGGREGATE REQUIREMENTS

Aggregate used in public road construction must meet specific engineering and physical property requirements. Aggregate specifications used throughout this paper are those required by the Virginia Department of Transportation (1987) as defined by the American Association of State Highway and Transportation Officials (AASHTO) and the American Society for Testing and Materials (ASTM).

Public highways and roads are constructed in multiple layers or courses (Figure 4). Each course has specific aggregate, materials, and construction requirements. The surface course (wearing course) made of asphalt concrete is designed to resist skidding, traffic abrasion, and the disintegrating effects of weathering. These design features determine the size, quality, and type of aggregate material used. As required by VDOT specifications, coarse aggregate (larger than No. 8 sieve) used in an asphalt surface course with more than 750 vehicles per day must meet the following conditions:

1. Aggregate must be non-polishing: To resist skidding, the aggregate must be non-polishing which refers to crushed rock that does not develop a smooth or slippery surface when exposed as part of the surface course. No small scale laboratory or engineering test is uniformly recognized in Virginia to define this characteristic. Acceptance of an aggregate classified as non-polishing is generally based on the historical performance of the stone in use on other road surfaces in the region. A simplified rule-of-thumb (which is generally accepted until proven otherwise) is that limestone and dolomite tend to polish; while sandstone, igneous, and metamorphic rocks such as granite gneiss and quartzite are generally classified as non-polishing.
2. Aggregate must meet Los Angeles Abrasion Test requirements: To resist traffic abrasion and crushing, the aggregate must be hard and durable. This characteristic is determined by the Los Angeles Abrasion Test which measures degradation of an aggregate sample caused by a combination of abrasion, grinding, impact, and crushing. Test results are expressed as a percentage loss of the original sample weight; thus a low Los Angeles abrasion loss indicates a high quality aggregate very resistant to abrasion. VDOT specifications require coarse aggregate used in asphalt surface courses to be Grade A or Grade B stone, having an abrasion loss of 45 percent or less at 500 revolutions (Table 1).
3. Aggregate must meet Magnesium Sulphate Soundness Test requirements: To resist the disintegrating effects of weathering, the aggregate must not show excessive



SANDSTONE UNITS IN SCOTT COUNTY, VIRGINIA
(modified after Geologic Map of Virginia, 1963)

Geology

Pl	--Lee Formation, undivided (includes the upper and lower quartzarenites of the Middlesboro Member
Mbh	--Bluestone and Hinton Formations, undivided (includes the Tallery and Stony Gap Sandstone Members of the Hinton Formation)
Mp	--Pennington Formation
Mcf	--Cove Creek Limestone and Fido Sandstone, undivided
Du	--Devonian formations, undivided (includes the Wildcat Valley Sandstone)
Stc	--Rose Hill Formation and Clinch Sandstone, undivided

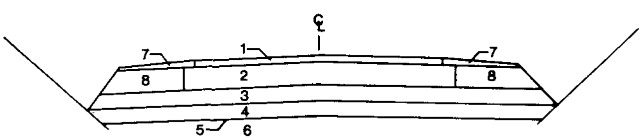
Sample Location

● --coarse non-polishing aggregate

Figure 3. Location map of active quarries that supply non-polishing aggregate into southwestern Virginia.

freeze-thaw breakdown. This characteristic is determined by the Magnesium Sulphate Soundness Test which measures degradation of an aggregate sample subject to weathering by simulating freeze-thaw activity. These test results are also expressed as a percentage loss of the original sample weight; thus a low soundness loss indicates a high quality aggregate very resistant to weathering breakdown. VDOT specifications require coarse aggregate used in asphalt surface courses to have a soundness loss of 15 percent or less in magnesium sulphate for 5 cycles (Table 2).

Although VDOT requires other specifications such as the amount of deleterious material, only abrasion loss and soundness results are presented in this study. This data will give an overview and characterize the sandstone formations with potential to be a source of non-polishing aggregate.



FLEXIBLE PAVEMENT CROSS-SECTION
(modified after National Crushed Stone Association Flexible Pavement Design Guide for Highways, 1972)

1. Surface Course, Asphalt Concrete
2. Base Course, Asphalt Concrete
3. Subbase, Aggregate
4. Subbase, Select Material
5. Subgrade Elevation
6. Roadbed Material
7. Shoulder Surfacing
8. Shoulder Base, Asphalt Concrete

Figure 4. Cross-section of a typical asphalt highway.

Table 1. Los Angeles abrasion loss requirements for coarse aggregate as used by the Virginia Department of Transportation (1987).

ABRASION

USE	Los Angeles Abrasion Loss, Maximum, Percent: 100 Rev.	Los Angeles Abrasion Loss, Maximum, Percent: 500 Rev.
Grade A Stone	9	40
Grade B Stone	12	45
Grade C Stone	14	50
Slag	12	45
Gravel	12	45

Table 2. Soundness loss requirements for coarse aggregate as used by the Virginia Department of Transportation (1987).

SOUNDNESS

USE	Soundness Loss, Maximum, Percent: Freeze and Thaw (20 Cycles)	Soundness Loss, Maximum, Percent: Magnesium Sulphate (5 Cycles)
Portland Cement Concrete	5	12
Asphalt Surface Courses	6	15
Asphalt and Aggregate Bases	7	20
Select Material (Type I) and Subbase	12	30

PROCEDURES

Many sandstone outcrops were examined. Composition ranged from quartzarenite and quartz-pebble conglomerate to micaceous and calcarenaceous sandstone. Only hard and well-cemented sandstones were sampled because non-polishing aggregate must be competent and resistant to abrasion. Representative chip samples were collected from selected outcrops and road cuts to form bulk samples weighing 60 to 80 pounds each. The bulk samples were first broken by hand and then crushed in a jaw crusher to produce a crusher-run type of sample made up of aggregate smaller than 2 inches in diameter. This prepared aggregate sample was then tested to determine abrasion resistance and soundness.

The Los Angeles Abrasion Loss test was conducted for all samples. The bulk aggregate samples were first sieved to determine size range (grading) of the crushed aggregate material. All samples qualified as Grading A, meeting the required splits of 1 1/2 to 1 inch, 1 to 3/4 inch, 3/4 to 1/2 inch, and 1/2 to 3/8 inch. Weighed aggregate was then tumbled with 12 steel spheres 1.84 inches in diameter in a hollow steel drum with a shelf plate. After 500 revolutions, the aggregate sample was removed, sieved, and weighed again. The difference between the original weight and the final weight of the sample is expressed as the percentage loss.

If the sandstone aggregate sample qualified as Grade A stone, it was then tested for soundness. First, the aggregate sample was sieved into three size splits of 1 1/2 to 3/4 inch, 3/4 to 3/8 inch, and 3/8 inch to U.S. Standard Sieve No. 4. Weighed aggregate was then soaked in a solution of magnesium sulphate for 16 to 18 hours and oven dried. After a total of 5 cycles, the aggregate sample was sieved and weighed again. The difference between the original weight and the final weight of the sample is expressed as a percentage loss. Results of the soundness test are given for each size split to characterize the three size ranges. Original grading, weight after test, weighted loss and total weighted loss were also calculated from laboratory data and are available.

All laboratory testing, including grading of the aggregate sample, abrasion loss, and soundness testing were performed in accordance with VDOT and AASHTO procedures.

DESCRIPTION AND ANALYSES OF SAMPLES

A brief discussion of the geologic formation or member will be followed by location, geologic description, and laboratory analyses for each sample. Location of the sample is designated by geographical location and Universal Transverse Mercator (UTM) coordinates. Geologic descriptions are from field data collected at the sample site. Bedding and splitting characteristics are described separately using the quantitative terms defined by McKee and Weir (1953). All samples were examined with a binocular microscope in addition to the Los Angeles abrasion and magnesium sulphate soundness tests. Selected samples were also analyzed by X-ray diffraction and X-ray fluorescence.

Detailed geologic maps (scale 1:24,000) were recently published for the northern portion of Scott County by Henika (1988), Nolde and Diffenbach (1988), and Whitlock and others (1988). These maps show the geology along the folded and faulted southeastern flank of the Pine Mountain fault block. This includes outcrop patterns of the Hinton and Lee Formations of Mississippian and Pennsylvanian age, and location of major structural features, such as the Hunter Valley fault and the Stone Mountain syncline, cited in this report.

CLINCH SANDSTONE

The Clinch Sandstone (Silurian) is found in southern, central, and western Scott County (Figure 2). It is a prominent ridge-forming unit exposed along Clinch Mountain in Scott County and throughout the Valley and Ridge province of southwestern Virginia. The formation ranges form 10 to 200 feet in thickness (Butts, 1940) and is generally very hard where fresh, friable where weathered, white to very-pale orange, very-fine to medium grained, locally conglomeratic, and medium to very-thick bedded. In the past, the Clinch Sandstone has been worked as a source of glass-grade sand, mortar sand, and sand used in ceramics and abrasives (Gildersleeve and Calver, 1945).

Three samples from the Clinch Sandstone were collected and analyzed for potential use as coarse aggregate (Figure 2). Los Angeles abrasion loss ranged from 56.6 to 83.8 percent (Table 3). No samples qualified for use as coarse non-polishing aggregate.

Table 3. Los Angeles abrasion loss for samples of sandstone aggregate collected in Scott County, Virginia.

LOS ANGELES ABRASION LOSS (percent loss at 500 revolutions)

Sample	Grading	% loss at 500 Rev.	Use
Clinch Sandstone			
27B-2	A	83.8	none
29A-6	A	56.6	none
60D-6	A	67.0	none
Fido Sandstone			
27A-1	A	19.5	Grade A Stone
27A-2	A	19.4	Grade A Stone
27A-3	A	17.3	Grade A Stone
Pennington Formation			
27C-1	A	23.6	Grade A Stone
28C-1	A	21.9	Grade A Stone
Stony Gap Sandstone Member			
29A-2	A	42.7	Grade B Stone
60D-8	A	33.4	Grade A Stone
Tallery Sandstone Member			
60C-6	A	86.3	none
60D-7	A	33.3	Grade A Stone
61D-3	A	85.2	none
lower quartzarenite of the Middlesboro Member			
59C-1	A	52.6	none
59C-3	A	40.1	Grade B Stone
59C-5	A	67.5	none
60C-1	A	51.2	none
60C-2	A	56.4	none
60C-3	A	57.8	none
60D-2	A	38.5	Grade A Stone
upper quartzarenite of the Middlesboro Member			
59B-1	A	42.9	Grade B Stone
59C-2	A	34.7	Grade A Stone
59C-4	A	40.2	Grade B Stone
60C-4	A	93.0	none
60D-1	A	59.1	none

Sample 27B-2

Location: The Clinch Sandstone was sampled 1.0 mile N25°E of Hilton, 2.0 miles N33°E of the intersection of State Roads 614 and 896 at Owen Corner, 6850 feet N15°E of bench mark BM U 217 (elevation 1315 feet) southwest of Hilton, at the inactive Hilton Sand Company quarry site, in the Hilton, Virginia 7.5-minute quadrangle (UTM: N4,058,760 E368,150; Zone 17).

Description: The sandstone is moderately well indurated to

friable, white to very-pale orange with minor grayish-orange banding, fine to medium grained, thin to very-thick bedded, and blocky to massive. The sample was collected from a 20-foot-thick interval of moderately well indurated sandstone exposed in the quarry. The strike is N70°E with a dip of 40°SE.
Laboratory analyses: The sand is fine to medium grained, angular to subrounded, and moderately well sorted. Los Angeles abrasion loss was 83.8 percent (Table 3).

Sample 29A-6

Location: The Clinch Sandstone was sampled 4.5 miles S85°W of Duffield, 1.3 miles N52°W of the intersection of State Roads 604 and 638 at Pattonsville, 1700 feet S88°W of bench mark BM SN 1520 (elevation 2170 feet), in the Duffield, Virginia 7.5-minute quadrangle (UTM: N4,064,260 E333,050; Zone 17).
Description: The sandstone is moderately well indurated, white to grayish-orange, fine grained, medium to very-thick bedded, and slabby to blocky. The sample was collected from a 12-foot-thick interval exposed north of the road. The strike is N56°E with a dip of 32°SE.
Laboratory analyses: The sand is very-fine grained, subangular to subrounded, and moderately well sorted. Los Angeles abrasion loss was 56.6 percent (Table 3).

Sample 60D-6

Location: The Clinch Sandstone was sampled 2.8 miles N15°W of Fort Blackmore, 1.0 mile N85°E of the intersection of State Roads 619 and 653 at Ka, 2100 feet S25°W of the survey marker Station B (elevation 1597 feet) west of New Buffalo Church, in the Fort Blackmore, Virginia 7.5-minute quadrangle (UTM: N4,075,060 E357,570; Zone 17).
Description: The sandstone is moderately well indurated, white to yellowish-orange with moderate brown banding, fine to medium grained, thin to thick bedded, and slabby to blocky. The sample was collected from a 25-foot-thick interval cropping out along the ridge. Strike is N40°E with a dip of 26°NW.
Laboratory analyses: The sand is fine grained, subangular, and moderately well sorted. Los Angeles abrasion loss was 67.0 percent (Table 3)

WILDCAT VALLEY SANDSTONE

The Wildcat Valley Sandstone (Devonian) is found in the western portion of Scott County (Figure 2). The formation is identified as Helderberg undivided by Butts (1940, p. 290), and more recently named Wildcat Valley Sandstone by Miller and others (1964). The Wildcat Valley sandstone is 40 to 60 feet thick, generally very friable in weathered outcrop, white to grayish-orange, very-fine to coarse grained, irregular bedded, and locally calcareous and fossiliferous with brachiopod fragments and molds.

No samples were collected and analyzed from the Wildcat Valley Sandstone because most of the formation exposed in Scott County is very friable and not suitable for coarse non-polishing aggregate.

FIDO SANDSTONE

The Fido Sandstone (Mississippian) is found in southeastern Scott County (Figure 2). Averitt (1941) reported the formation as being 35 to 50 feet thick where it crops out along the limbs of the Early Grove anticline. However, gas well data from the Early Grove area indicates the formation is as much as 120 feet thick, and averages 60 to 75 feet in thickness. The sandstone is very hard when fresh, locally friable when weathered, grayish-red to very-dusky red, thin to very-thick bedded, flaggy to massive, calcareous, and fine to coarse grained with thin interbeds of fossil and rock fragments. Samples of the Fido Sandstone analyzed by X-ray diffraction contained quartz, calcite, muscovite, plagioclase, chlorite, and microcline (O.M. Fordham, 1988, written communication). Analysis of the same samples by X-ray fluorescence reported 49.4 to 55.7 percent SiO_2 and 30.7 to 34.6 percent $CaCO_3$ (O.M. Fordham, 1988, written communication). In thin section, the rock is very-fine to coarse grained with angular to subrounded grains of quartz, fossil fragments, calcite, feldspar, mica, chlorite, and a fine matrix of silt and calcareous material.

Three samples from the Fido Sandstone were collected and analyzed for potential use as coarse aggregate (Figure 2). Los Angeles abrasion loss ranged from 17.3 to 19.5 percent (Table 3). Soundness loss of Grade A Stone ranged from 0.2 to 2.4 percent (Table 4). Based upon abrasion and soundness loss tests, all three samples (27A-1, 27A-2, and 27A-3) qualified for use as coarse non-polishing aggregate. However, skid-pad tests are recommended to fully qualify this rock as non-polishing because of the high calcium carbonate ($CaCO_3$) content.

Sample 27A-1

Location: The Fido Sandstone was sampled 4.9 miles S20°W of Mendota, 0.4 mile N18°E of Shelleys, 900 feet S5°W of bench mark BM T 186 (elevation 1483) along Ketron Branch Creek, in the Mendota, Virginia 7.5-minute quadrangle (UTM: N4,055,900 E380,560; Zone 17).
Description: The sandstone is very-well indurated, grayish-red to very-dusky red, fine to medium grained, calcareous, thin to very-thick bedded, and flaggy to massive. The sample was collected from a 15-foot-thick interval exposed in a road cut on the west side of U.S. Highway 58/421. No strike or dip was measured at the outcrop. Regional strike is N40°E with a dip of 12°NW, along the northwestern limb of the Early Grove anticline.
Laboratory analyses: The sand is fine grained, subangular, and poorly sorted with fossil fragments, mica, and feldspar. X-ray diffraction of the sample identified the mineral content to be quartz, calcite, muscovite, plagioclase, chlorite, and microcline. X-ray fluorescence determined that the sample contained 55.7 percent SiO_2 and 30.7 percent $CaCO_3$. Los Angeles abrasion loss was 19.5 percent, which qualified this sample as Grade A Stone (Table 3). Soundness loss ranged from 0.2 to 1.3 percent (Table 4).

Table 4. Soundness loss for samples of Grade A sandstone aggregate collected in Scott County, Virginia

	SOUNDNESS LOSS (percent loss in magnesium sulphate—5 cycles)		
Sample	1 1/2 to 3/4 inch	3/4 to 3/8 inch	3/8 inch to #4
Fido Sandstone			
27A-1	0.2	0.4	1.3
27A-2	0.2	0.6	1.2
27A-3	0.6	0.8	2.4
Pennington Formation			
27C-1	0.7	1.5	5.2
28C-1	1.6	2.2	4.3
Stony Gap Sandstone Member			
60D-8	0.7	4.1	14.9
Tallery Sandstone Member			
60D-7	0.4	1.6	12.0
lower quartzarenite of the Middlesboro Member			
60D-2	5.6	13.8	50.4
upper quartzarenite of the Middlesboro Member			
59C-2	0.9	1.6	11.1

Sample 27A-2

Location: The Fido Sandstone was sampled 4.8 miles S21°W of Mendota, 0.6 mile N15°E of Shelleys, 200 feet S16°W of bench mark BM T 186 (elevation 1483) along Ketron Branch Creek, in the Mendota, Virginia 7.5-minute quadrangle (UTM: N4,056,120 E380,570; Zone 17).
Description: The sandstone is very-well indurated, grayish-red to dusky red, fine to coarse grained with rock and fossil fragments, calcareous, very-thin to thick bedded and flaggy to blocky. The sample was collected from a 12-foot-thick interval exposed in a road cut on the west side of U.S. Highway 58 and 421. No strike or dip was measured at the outcrop. Regional strike is N40°E with a dip of 12°NW, along the northwest limb of the Early Grove anticline.
Laboratory analyses: The sand is very-fine to fine grained, subangular, and poorly sorted with coarse fossil and rock fragments. X-ray diffraction of the sample identified the mineral content to be quartz, calcite, muscovite, plagioclase, chlorite, and microcline. X-ray fluorescence determined that the sample contained 52.0 percent SiO_2 and 30.9 percent $CaCO_3$. Los Angeles abrasion loss was 19.4 percent, which qualified this sample as Grade A Stone (Table 3). Soundness loss ranged from 0.2 to 1.2 percent (Table 4).

Sample 27A-3

Location: The Fido Sandstone was sampled 5.5 miles S18°W of Mendota, 0.6 mile S12°W of the bench mark BM T 186 (elevation 1483) along Ketron Branch Creek, 1150 feet N43°E of the bench mark BM C 185 (elevation 1503 feet) on State Road 617, at Shelleys, in the Mendota, Virginia 7.5-minute quadrangle (UTM: N4,055,250 E380,380; Zone 17).
Description: The sandstone is very-well indurated, grayish-red to very dark red, very-fine to coarse grained with rock and fossil fragments, calcareous, thin to very-thick bedded, and flaggy to blocky. The sample was collected from a 14-foot-thick interval exposed in a road cut on the east side of U.S. Highway 58 and 421. Strike is N51°E with a dip of 10°SE, along the southeastern limb of the Early Grove anticline.
Laboratory analyses: The sand is very-fine to medium grained, subangular, and poorly sorted with coarse fossil fragments, feldspar, and mica. X-ray diffraction of the sample identified the mineral content to be quartz, calcite, muscovite, plagioclase, chlorite, and microcline. X-ray fluorescence determined that the sample contained 49.4 percent SiO_2 and 34.6 percent $CaCO_3$. Los Angeles abrasion loss was 17.3 percent, which qualified this sample as Grade A Stone (Table 3). Soundness loss ranged from 0.6 to 2.4 percent (Table 4).

PENNINGTON FORMATION

The Pennington Formation (Mississippian), found in the southern portion of Scott County (Figure 2), is stratigraphically equivalent to the Bluestone and Hinton Formations. The Pennington Formation a sequence of shales, siltstones, and sandstones is about 2,250 feet thick in the Early Grove area of Virginia (Averitt, 1941). Sandstones are regionally discontinuous, light gray to red, fine to coarse grained, medium to very-thick bedded, flaggy to massive, and locally interbedded with shale.

Two samples from the Pennington Formation were collected and analyzed for potential use as coarse aggregate (Figure 2). Los Angeles abrasion loss ranged from 21.9 to 23.6 percent (Table 3). Soundness loss of selected Grade A Stone ranged from 0.7 to 5.2 percent (Table 4). Both samples (27C-1 and 28C-1) qualified for use as coarse non-polishing aggregate.

Sample 27C-1

Location: A sandstone in the Pennington Formation was sampled 3.1 miles N65°E of Bloomingdale, Tennessee, 1.0 mile S70°W of the intersection of State Roads 693 and 696 along Roberts Creek, 4700 feet N30°E of the intersection of State Roads 698 and 704 along Timbertree Creek, in the Indian Springs, Tennessee-Virginia 7.5-minute quadrangle (UTM: N4,052,100 E371,480; Zone 17).
Description: The sandstone is well indurated, dark gray to grayish-red and brownish-gray, slightly calcareous, fine

grained, thin to very-thick bedded, and flaggy to blocky. The sample was collected from a 15-foot-thick interval along a road cut south of the road. Strike is N82°E with a dip of 28°SE.
Laboratory analyses: The sand is very-fine grained, subangular to subrounded, and well sorted. Los Angeles abrasion loss was 23.6 percent, which qualified this sample as Grade A Stone (Table 3). Soundness loss ranged from 0.7 to 5.2 percent (Table 4). This sample met the requirements for use as coarse non-polishing aggregate.

Sample 28C-1

Location: A sandstone in the Pennington Formation was sampled 4.0 miles S65°E of Kermit, 0.4 mile N20°W of Cameron Church at the intersection of Stanley Valley and Possum Creek, 1200 feet S25°E of the intersection of State Roads 632 and 637, in the Church Hill, Tennessee-Virginia 7.5-minute quadrangle (UTM: N4,051,680 E351,680; Zone 17).
Description: The sandstone is well indurated, medium gray to brownish-gray, slightly calcareous, fine grained, thin to medium bedded, and flaggy to blocky. The sample was collected from a 20-foot-thick interval along a road cut east of the road. Strike is N80°E with a dip of 34°SE.
Laboratory analyses: The sand is very-fine grained, vitreous, subangular, and well sorted. Los Angeles abrasion loss was 21.9 percent, which qualified this sample as Grade A Stone (Table 3). Soundness loss ranged from 1.6 to 4.3 percent (Table 4). The sample met the requirements for use as coarse non-polishing aggregate.

HINTON FORMATION

The Hinton Formation (Mississippian) is found in northern Scott County, adjacent to the Lee Formation (Figure 2). The Hinton ranges from 550 to 700 feet in thickness and is divided into four units: The Stony Gap Sandstone Member, the middle red member, the Little Stone Gap Member, and the Tallery Sandstone Member. The sandstone members are very-fine to medium grained, quartzose, locally conglomeratic, and range from 55 to 420 feet in thickness. The middle red member contains yellowish-brown to reddish-brown siltstones and shales, and ranges from 165 to 370 feet thick. The Little Stone Gap Member is a fossiliferous and calcareous mudstone and clayshale as much as 45 feet thick. The Stone Gap and Tallery Sandstone Members of the Hinton Formation were sampled and are described below.

Stony Gap Sandstone Member

The Stony Gap Sandstone Member of the Hinton Formation is found in Northern Scott County (Figure 2). It is the lowermost member of the Hinton and ranges from 160 to 420 feet in thickness. The sandstone is friable to well indurated, light gray to yellowish-gray and pale orange, very-fine to medium grained, thin to thick bedded with tabular and planar cross beds, and flaggy to blocky.

Two samples from the Stony Gap Sandstone Member were collected and analyzed for potential use as coarse aggregate (Figure 2). Los Angeles abrasion loss ranged from 33.4 to 42.7 percent (Table 3). Soundness loss of selected Grade A Stone ranged from 0.7 to 14.9 percent (Table 4). One sample (60D-8) qualified for use as coarse non-polishing aggregate.

Sample 29A-2

Location: The Stony Gap Sandstone Member was sampled 2.5 miles N35°E of Duffield, 1.2 miles N35°W of the intersection of State Roads 653 and 871 at Sunbright, 3300 feet N20°W of the intersection of State Roads 654 and 775, east of Dry Branch, in the Duffield, Virginia 7.5-minute quadrangle (UTM: N4,067,900 E341,580; Zone 17).
Description: The sandstone is well indurated, very-pale orange to yellowish-gray with minor dusky red iron-oxide staining along bedding planes, very-fine to fine grained thin to thick bedded, and flaggy to blocky. The sample was collected from the lower 70-foot-thick interval of a large, thick outcrop exposed along Dry Branch. Strike is N15°E with a dip of 10°NE.
Laboratory analyses: The sand is very-fine grained, vitreous, subangular, and well sorted. Los Angeles abrasion loss was 42.7 percent, which qualified this sample as Grade B Stone (Table 3).

Sample 60D-8

Location: The Stony Gap Sandstone Member was sampled 6.3 miles N45°E of Fort Blackmore, 1.1 miles N35° east of the intersection of State Roads 653 and 680, 2700 feet S73°E of the survey marker MLB 1375 (elevation 2560 feet) west of Indian Grave Gap, in the Fort Blackmore, Virginia 7.5-minute quadrangle (UTM: N4,078,100 E365,840; Zone 17).
Description: The sandstone is well indurated, very-light gray to yellowish-gray with minor very-dark red iron-oxide staining along bedding planes, very-fine to fine grained, thin to thick bedded, and flaggy to blocky. The sample was collected from a 40-foot-thick interval of outcrop east of the road. Strike is N74°E with an approximate dip of 50° to the northwest near the axis of a tightly folded overturned anticline between the Stone Mountain syncline and the Hunter Valley fault.
Laboratory analyses: The sand is very-fine grained, vitreous, subangular to subrounded, and well sorted. Los Angeles abrasion loss was 33.4 percent, which qualified this sample as Grade A Stone (Table 3). Soundness loss ranged from 0.7 to 14.9 percent (Table 4). This sample met the requirements for use as coarse non-polishing aggregate.

Tallery Sandstone Member

The Tallery Sandstone Member of the Hinton Formation is found in northern Scott County (Figure 2). The Tallery Sandstone is the uppermost member of the Hinton and ranges from 55 to 125 feet in thickness. The sandstone is friable to well indurated, white to pale orange, fine to coarse grained, quartzose, locally granular to conglomeratic, thin to very-thick bedded, and flaggy to massive.

Three samples from the Tallery Sandstone Member were collected and analyzed for potential use as coarse aggregate. Los Angeles abrasion loss ranged from 33.3 to 86.3 percent (Table 3). Soundness loss of selected Grade A Stone ranged from 0.4 to 12.0 percent (Table 4). One sample (60D-7) qualified for use as coarse non-polishing aggregate.

Sample 60C-6

Location: The Tallery Sandstone Member was sampled 2.7 miles S20°E of East Stone Gap, 1.5 miles S30°W of the intersection of State Roads 616 and 722 at Cracker Neck, 2800 feet N45°W of the survey marker Wise No. 6 (elevation 3456 feet) on Little Mountain, at Maple Gap in the East Stone Gap, Virginia 7.5-minute quadrangle (UTM: N4,077,120 E346,070; Zone 17).
Description: The sandstone is well indurated, white to grayish-orange, fine to coarse grained, conglomeratic, thin to very-thick bedded, and flaggy to blocky. Well-rounded spherical quartz pebbles 0.1 to 0.25 inches in diameter are scattered throughout the exposure and concentrated in 1- to 2-inch beds. The sample was collected from a 30-foot-thick interval of outcrop. Strike is N48°E with a dip of 4°SE on the relatively flat-lying rocks on the north limb of the Stone Mountain syncline.
Laboratory analyses: The sand is very-fine to fine grained, subangular to rounded, and moderately sorted with coarse grains and small quartz pebbles. Los Angeles abrasion loss was 86.3 percent (Table 3).

Sample 60D-7

Location: The Tallery Sandstone Member was sampled 5.5 miles N35°E of Fort Blackmore, 1.7 miles S5°W of Corder Bottom Lake, 4000 feet S72°W of the survey marker MLB 1375 (elevation 2560 feet) west of Indiana Grave Gap, along McGhee Creek, in the Fort Blackmore, Virginia 7.5-minute quadrangle (UTM: N4,078,030 E363,880; Zone 17).
Description: The sandstone is well indurated, very-pale orange to yellowish-gray, very-fine to fine grained, thin to very-thick bedded, and flaggy to blocky. The sample was collected from a 50- to 60-foot-thick interval cropping out east of the road. Strike is east-west and beds are overturned with a dip of 80°S on the overturned south limb of the Stone Mountain syncline.
Laboratory analyses: The sand is very-fine grained, vitreous, subangular to subrounded, and well sorted. Los Angeles abrasion loss was 33.3 percent, which qualified this sample as Grade A Stone (Table 3). Soundness loss ranged from 0.4 to 12.0 percent (Table 4). This sample met the requirements for use as coarse non-polishing aggregate.

Sample 61D-3

Location: The Tallery Sandstone Member was sampled 1.8 miles N87°E of Tito, 0.6 mile N50°E of Bowen Chapel, 6400 feet S26°E of the survey marker Bowling (elevation 3557 feet) on Bowling Knob, on the northwest side of Mill Hollow, in the Big Stone Gap, Virginia 7.5-minute quadrangle (UTM: N4,069,530 E 340,990; Zone 17).
Description: The sandstone is moderately well indurated, white to grayish-orange with grayish-red iron-oxide staining, fine to granular grained, conglomeratic, medium to very-thick bedded and flaggy to massive. Well-rounded spherical to oval quartz pebbles 0.1 to 0.5 inch in diameter are scattered throughout the outcrop and concentrated in beds less that 12 inches thick. The sample was collected from a 30-foot-thick interval of outcrop. Strike is N20°W with a dip of 12°NE.
Laboratory analyses: The sand is very-fine grained to granular, subangular to subrounded, and poorly sorted with small quartz pebbles. Los Angeles abrasion loss was 85.2 percent (Table 3).

LEE FORMATION

The Lee Formation (Pennsylvanian) is found in the northern portion of Scott County (Figure 2). It is exposed along Stone Mountain on the southeast flank of the Powell Valley anticline. In most of the Appalachian Plateaus province of southwestern Virginia, the Lee Formation is divided into the Middlesboro, Hensley, and Bee Rock Sandstone Members. The top of the Lee Formation is marked by the upper quartzarenite tongue of the Middlesboro Member in this area because the Bee Rock Sandstone Member is not present (Henika, 1988; Whitlock and others, 1988; Nolde and Diffenbach, 1988). The base of the overlying Norton Formation is therefore lowered to the top of the Middlesboro Member; and the Lee Formation consists only of a lower quartzarenite, a middle siltstone, and an upper quartzarenite in the Middlesboro Member. The lower and upper quartzarenite units of the Middlesboro Member were examined and sampled.

Lower quartzarenite of the Middlesboro Member

The lower quartzarenite of the Middlesboro Member of the Lee Formation (Pennsylvanian) is 150 to 250 feet thick. It lies below the middle siltstone unit of the Middlesboro Member, a 330- to 700-foot-thick sequence of shales, siltstones, sandstones, and coal beds. The lower quartzarenite is very-light gray to very-pale orange, fine to coarse grained, locally conglomeratic, thin to very-thick bedded with tabular and planar cross-beds, and platy to massive. Well-rounded spherical to oval quartz pebbles commonly occur in discontinuous lenses and scour channels in the lower portion of the unit. The quartzarenite may locally be interbedded with shales, siltstones, and coal beds.

Seven samples from the lower quartzarenite of the Middlesboro Member were collected and analyzed for potential use as coarse aggregate. Los Angeles abrasion loss ranged from 38.5 to 67.5 percent (Table 3). Soundness loss of selected Grade A Stone ranged from 5.6 to 50.4 percent (Table 4). No samples fully qualified for use as coarse non-polishing aggregate.

Sample 59C-1

Location: The lower quartzarenite of the Middlesboro Member

was sampled 2.4 miles N30°E of Dungannon, 1.2 miles S40°W of the intersection of State Highway 72 and State Road 723, 3000 feet N16°E of the intersection of State Highway 72 and State Road 608, in the Dungannon, Virginia 7.5-minute quadrangle (UTM: N4,079,920 E371,040; Zone 17).
Description: The quartzarenite is well indurated, very-light gray to very-pale orange, fine to coarse grained, conglomeratic, thin to very-thick bedded, and blocky to massive. Well-rounded spherical to oval quartz pebbles 0.25 to 0.75 inch in diameter occur in lenses up to 3 feet thick. The sample was collected from a 40-foot-thick interval exposed in a road cut. Strike is N55°W with a dip of 36°NE along the axis of an overturned anticline in the tightly folded rocks on the south limb of the Stone Mountain syncline.
Laboratory analyses: The sand is fine to coarse grained subrounded, and poorly sorted with small to large quartz pebbles. Los Angeles abrasion loss was 52.6 percent (Table 3).

Sample 59C-3

Location: The lower quartzarenite of the Middlesboro Member was sampled 4.5 miles N55°E of Dungannon, 1.5 miles S85°W of the intersection of State Highway 72 and State Road 723, 2400 feet N35°E of the water tower at Miller Yard, in the Dungannon, Virginia 7.5-minute quadrangle (UTM: N4,080,990 E374,660; Zone 17).
Description: The quartzarenite is well indurated, very pale orange to yellowish-gray, medium to coarse grained, conglomeratic, thin to very-thick bedded, and flaggy to blocky. Iron-oxide stained well-rounded spherical to oval quartz pebbles 0.25 to 1 inch in diameter locally make up as much as 40 percent of the rock in 3- to 4-foot-thick lenses. The sample was collected from a 30-foot-thick interval exposed in a railroad cut west of the Clinchfield Railroad. Strike is N65°E and beds are overturned with a dip of 30°SE on the overturned south limb of the Stone Mountain syncline, north of the Hunter Valley fault.
Laboratory analyses: The sand is fine to coarse grained, subangular to subrounded, and poorly sorted with large quartz pebbles. Los Angeles abrasion loss was 40.1 percent, which qualified this sample as Grade B Stone (Table 3).

Sample 59C-5

Location: The lower quartzarenite of the Middlesboro Member was sampled 2.0 miles N30°W of Dungannon, 1.5 miles S45°W of the intersection of State Highway 72 and State Road 653, 3200 feet N17°E of the survey marker MLB 1374 (elevation 2112 feet) south of Dry Creek, in the Dungannon, Virginia 7.5-minute quadrangle (UTM: N4,079,460 E367,610; Zone 17).
Description: The quartzarenite is well indurated, very-light gray to very-pale orange, medium to coarse grained, conglomeratic, medium to very thick bedded, and slabby to blocky. Well-rounded spherical to oval quartz pebbles 0.25 to 0.75 inch in diameter are scattered throughout the exposure and concentrated in 1- to 2-foot-thick lenses. The sample was collected from a 25-foot-thick interval of outcrop exposed west of the jeep trail. Strike is N60°E and beds are overturned with a dip of 56°SE on the overturned south limb of the Stone Mountain syncline.
Laboratory analyses: The sand is fine to coarse grained, subrounded, and poorly sorted with coarse granular sand and quartz pebbles. Los Angeles abrasion loss was 67.5 percent (Table 3).

Sample 60C-1

Location: The lower quartzarenite of the Middlesboro Member was sampled 2.3 miles N85°W of Stanleytown, 0.5 mile N20°W of the intersection of State Roads 653 and 725, 2400 feet N27°W of the bench mark BM 1684 (elevation 1684 feet) east of State Road 725, in the East Stone Gap, Virginia 7.5-minute quadrangle (UTM: N4,071,100 E345,540; Zone 17).
Description: The quartzarenite is well indurated, light gray to very-pale orange, medium to coarse grained, conglomeratic, medium to very thick bedded, and flaggy to massive. Well-rounded spherical quartz pebbles 0.1 to 0.5 inch in diameter are scattered throughout the exposure and concentrated in lenses up to 5 feet thick. The sample was collected in the lower 50-foot-thick interval exposed in a large outcrop and road cut. Strike is N64°E with a dip of 12°SE on the relatively flat-lying north limb of the Stone Mountain syncline.
Laboratory analyses: The sand is fine grained to granular, subrounded, and poorly sorted with coarse sand and quartz pebbles. Los Angeles abrasion loss was 51.2 percent (Table 3).

Sample 60C-2

Location: The lower quartzarenite of the Middlesboro Member was sampled 1.9 miles N17°W of Stanleytown, 1.4 miles N8°E of the intersection of State Roads 602 and 653, 6500 feet S3°W of the survey marker MLB 1565 (elevation 3327 feet) on Good Spur Ridge, in the East Stone Gap, Virginia 7.5-minute quadrangle (UTM: N4,073,480 E348,350; Zone 17).
Description: The quartzarenite is well indurated, very light gray to very-pale orange, fine to medium grained, conglomeratic, medium to thick bedded, and slabby to blocky. Well-rounded spherical quartz pebbles as much as 0.75 inch in diameter are found locally along thin pebble lags. The sample was collected from a 30- to 40-foot thick interval cropping out west of Cove Creek. Strike is N63°E with a dip of 10°SE on the relatively flat-lying northern limb of the Stone Mountain syncline.
Laboratory analyses: The sand is fine grained, subangular to subrounded, and moderately sorted with quartz pebbles. Los Angeles abrasion loss was 56.4 percent (Table 3).

Sample 60C-3

Location: The lower quartzarenite of the Middlesboro Member was sampled 5.3 miles N40°E of Stanleytown, 3.7 miles N30°E of the intersection of State Roads 653 and 656, 9600 feet S72°E of the survey marker Powell (elevation 3490 feet) at Cox Place, along Straight Fork, in the East Stone Gap, Virginia, 7.5-minute quadrangle (UTM: N4,077,300 E

354,470; Zone 17).
Description: The quartzarenite is well indurated, very light gray to very pale orange, fine to medium grained, conglomeratic, medium to very-thick bedded, and flaggy to blocky. Well-rounded spherical quartz pebbles as much as 0.5 inch in diameter occur in lenses 3 to 5 feet thick. The sample was collected from a 60-foot-thick interval of outcrop. Strike is N80°E with a dip of 12°SE on the relatively flat-lying north limb of the Stone Mountain syncline.
Laboratory analyses: The sand is fine grained, subangular to subrounded, and moderately sorted with quartz pebbles. Los Angeles abrasion loss was 57.8 percent (Table 3).

Sample 60D-2

Location: The lower quartzarenite of the Middlesboro Member was sampled 1.9 miles N30°E of Ka, 1.7 miles N50°E of the intersection of State Roads 619 and 657, 5950 feet N5°W of the survey marker Station B (elevation 1597 feet) on State Road 653 west of the New Buffalo Church, on Stony Creek, in the Fort Blackmore, Virginia 7.5-minute quadrangle (UTM: N4,077,410 E357,720; Zone 17).
Description: The quartzarenite is well indurated, very-pale orange to pinkish-gray, fine grained, thin to thick bedded, and platy to blocky. The sample was collected from a 50-foot-thick interval that crops out along Stony Creek. Strike is N44°E with a dip of 4°NW on the relatively flat-lying north limb of the Stone Mountain syncline.
Laboratory analyses: The sand is fine grained, subangular to subrounded, and well sorted. Los Angeles abrasion loss was 38.5 percent, which qualified this sample as Grade A Stone (Table 3). Soundness loss ranged from 5.6 to 50.4 percent (Table 4). The two coarse splits of aggregate from this sample met the requirements for use as coarse non-polishing aggregate, but crushed stone less than 3/8 inch could not be used.

Upper quartzarenite of the Middlesboro Member

The upper quartzarenite of the Middlesboro Member of the Lee Formation (Pennsylvanian) is as much as 100 to 250 feet thick, but the upper-most beds have commonly been removed by erosion where it is exposed along ridge tops in northern Scott County (Figure 2). The upper quartzarenite is generally very-light gray to yellowish-gray, fine to coarse grained, thin to very-thick bedded with large tabular to planar cross-beds, conglomeratic near the base, and flaggy to blocky. The upper part of the unit is finer grained, non-conglomeratic, and more uniform bedded than the lower part. Conglomerate beds are irregular and discontinuous, generally less than 5 feet thick, with irregular pebble lags along scour channels. Well-rounded spherical to oval quartz pebbles range from less than 0.25 up to 1.5 inches in diameter, and make up less than 10 percent of the total rock when averaged over a 5- to 10-foot-thick interval.

Five samples from the upper quartzarenite of the Middlesboro Member were collected and analyzed for potential use as coarse aggregate. Los Angeles abrasion loss ranged from 34.7 to 93.0 percent (Table 3). Soundness loss of selected Grade A Stone ranged from 0.9 to 11.1 percent (Table 4). One sample (59C-2) qualified for use as coarse non-polishing aggregate.

Sample 59B-1

Location: The upper quartzarenite of the Middlesboro Member was sampled 4.5 miles south of Coeburn, 1.6 miles S75°W of the intersection of State Highway 72 and State Road 755, 400 feet west of Little Stony Creek in the Coeburn, Virginia 7.5-minute quadrangle (UTM: N4,081,820 E369,490; Zone 17).
Description: The quartzarenite is well indurated, light gray to grayish-orange, fine grained, locally conglomeratic, thin to thick bedded, and flaggy to slabby. A few well-rounded spherical quartz pebbles less than 0.5 inch in diameter are along some bedding planes locally. The sample was collected from a 25-foot-thick interval of outcrop. Strike is N40°E with a dip of 4°SE on the relatively flat-lying north limb of the Stone Mountain syncline.
Laboratory analyses: The sand is fine grained, subangular to subrounded, and moderately well sorted. Los Angeles abrasion loss was 42.9 percent, which qualified this sample as Grade B Stone (Table 3).

Sample 59C-2

Location: The upper quartzarenite of the Middlesboro Member was sampled 3.3 miles N35°E of Dungannon, 1.3 miles N80°W of Miller Yard, 2200 feet S30°W of the intersection of State Highway 72 and State Road 723, in the Dungannon, Virginia 7.5-minute quadrangle (UTM: N4,080,700 E371,910; Zone 17).
Description: The quartzarenite is well indurated, very light gray to pinkish-gray with dusky red iron-oxide staining along bedding planes and on quartz pebbles, fine to coarse grained, conglomeratic, thin to thick bedded, and flaggy to blocky. A few well-rounded spherical to oval quartz pebbles as much as 0.25 inch in diameter are found along pebble lags. The sample was collected from a 30-foot-thick interval exposed in a road cut east of the highway. Strike is N41°E and beds are overturned with a dip of 46°SE on the overturned south limb of the Stone Mountain syncline.
Laboratory analyses: The sand is fine to coarse grained, subrounded to rounded, and poorly sorted with small quartz pebbles. Los Angeles abrasion loss was 34.7 percent, which qualified this sample as Grade A Stone (Table 3). Soundness loss ranged from 0.9 to 11.1 percent (Table 4). This sample met the requirements for use as coarse non-polishing aggregate.

Sample 59C-4

Location: The upper quartzarenite of the Middlesboro Member was sampled 4.5 miles N50°E of Dungannon, 0.6 mile N20°E of Miller Yard, 7600 feet east of the intersection of State Highway 72 and State Road 723, just east of the Clinchfield Railroad, in the Dungannon, Virginia 7.5-minute quadrangle (UTM: N4,081,320 E374,500; Zone 17).
Description: The quartzarenite is well indurated, light gray to

grayish-orange with grayish-red iron-oxide stains, fine to medium grained, locally conglomeratic, thin to very-thick bedded, and flaggy to blocky. Well-rounded spherical quartz pebbles as much as 0.5 inch in diameter are scattered in 1- to 4-foot-thick lenses. The sample was collected from a 60-foot-thick interval of outcrop. Strike is N47°E with a dip of 40°NW along the folded and faulted axis of the Stone Mountain syncline.
Laboratory analyses: The sand is fine grained, subangular to subrounded, and poorly sorted with quartz pebbles. Los Angeles abrasion loss was 40.2 percent, which qualified this sample as Grade B Stone (Table 3).

Sample 60C-4

Location: The upper quartzarenite of the Middlesboro Member was sampled 4.5 miles S65°E of East Stone Gap, southwest of Cox Place, 2100 feet S61°W of the survey marker Powell (elevation 3490 feet), in the East Stone Gap, Virginia 7.5-minute quadrangle (UTM: N4,078,000 E351,120; Zone 17).
Description: The quartzarenite is moderately indurated to friable, light gray to yellowish-gray, fine to medium grained, thin to thick bedded, and flaggy to blocky. A few small quartz pebbles as much as 0.25 inch in diameter are scattered throughout the rock. The sample was collected from a 20-foot-thick interval of outcrop. Strike is N60°E with a dip of 15°SE along the shallow dipping north limb of the Stone Mountain syncline.
Laboratory analyses: The sand is fine grained, subrounded, and moderately well sorted with small quartz pebbles. Los Angeles abrasion loss was 93.0 percent (Table 3).

Sample 60D-1

Location: The upper quartzarenite of the Middlesboro Member was sampled 7.0 miles N45°E of Fort Blackmore, 0.8 miles S45°E of Corder Bottom Lake, 5200 feet N5°E of the survey marker MLB 1375 (elevation 2560 feet) west of Indiana Grave Gap, in the Fort Blackmore, Virginia 7.5-minute quadrangle (UTM: N4,079,930 E365,240; Zone 17).
Description: The quartzarenite is well indurated to friable, very-light gray to light brownish-gray, fine to coarse grained, locally conglomeratic, thin to thick bedded, and flaggy to blocky. Well-rounded spherical to oval quartz pebbles as much as 1 inch in diameter are found locally in lenses 1 to 12 inches thick. The sample was collected from a well indurated 20-foot-thick interval of outcrop. Strike is N6°E with a dip of 3°SE along the relatively flat-lying north limb of the Stone Mountain syncline.
Laboratory analysis: The sand is fine grained, subangular to subrounded, and moderately sorted with large quartz pebbles. Los Angeles abrasion loss was 59.1 percent (Table 3).

SUMMARY

The major sandstone formations in Scott County were evaluated to identify additional sources of non-polishing aggregate in southwestern Virginia for use in highway construction.

Eight samples from the Fido Sandstone, and Pennington, Hinton, and Lee Formations qualified as non-polishing aggregate for use in an asphalt surface course. This is contrary to the generally accepted conclusion that sandstones from the Valley and Ridge and Appalachian Plateaus provinces of southwestern Virginia could not meet the required physical properties specifications. Evaluation of the Clinch and Wildcat Valley Sandstones, and selected portions of the Hinton and Lee Formations indicate that these rocks may not be good sources of high quality aggregate.

Los Angeles abrasion and soundness loss test results for samples from the Hinton and Lee Formations collected along the southeast flank of the Pine Mountain fault block show much variation. The folded and faulted rocks along the axis and overturned south limb of the Stone Mountain syncline tend to be much harder and more resistant to weathering, and have a lower Los Angeles abrasion loss (indicating a more competent and higher quality aggregate) than relatively flat-lying rocks on the north limb of the Stone Mountain syncline. The sandstones on the north limb tend to be more weathered and friable, and have a higher Los Angeles abrasion loss (indicating a less competent and lower quality aggregate). Los Angeles abrasion loss was 33.4 percent for folded rocks and 42.7 percent for flat-lying rocks from the Stony Gap Sandstone; 33.3 percent for folded rocks and 85.2 to 86.2 percent for flat-lying rocks from the Tallery Sandstone; 40.1 to 67.5 percent for folded rocks and 38.5 to 57.8 percent for flat-lying rocks from the lower quartzarenite of the Middlesboro Member; and 37.3 to 40.2 percent for folded rocks and 42.9 to 93.0 percent for flat-lying rocks and the upper quartzarenite of the Middlesboro Member. The folded and faulted rocks on the overturned south limb of the syncline have apparently undergone additional structural stresses and compression which have enhanced the physical properties of hardness and resistance.

Results of this study indicate that selected sandstones in Scott County have very good potential to be a source of non-polishing aggregate. Laboratory test results show there are variations in the quality of aggregate between the different formations, and within each formation or member. For this reason, a detailed geologic evaluation of all sandstone deposits should be made before commercial development.

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VIRGINIA CARBONATE ROCKS AND SAMPLING PROJECT

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ABSTRACT

Virginia has abundant reserves of carbonate rocks. Limestones and dolostones form a large portion of the surface formations in the Valley and Ridge province of Virginia. Minor occurrences of carbonate rocks are also found in the Piedmont province as limestone and marble and in the Coastal Plain province as shell deposits.

In 1987, 52 quarries and 2 underground mines produced 21,242,600 short tons of carbonate material. Major uses for high-purity limestone supplied by Virginia operations include lime to treat water and sewage, in the paper and steel industries, and for agricultural use to stabilize soil and to enhance its fertility. Environmentally oriented markets include use in control of sulfur and nitrogen emissions from stacks of coal-fired boilers, and acid-control stone. Other markets utilizing high-purity carbonate-rock products include cement-mortar manufacture; glass and steel industries; and fillers and extenders such as in fertilizer, animal feed, wallboard joint compound, paint, rug backing, anti-stick agents, the manufacture of chemicals, and rubber. Major markets not requiring high-purity carbonate rocks include aggregate stone for concrete, asphalt, highway base mix, concrete block, railroad ballast, soil-fertility enhancement, and for coal-mine dust.

In 1981, the Virginia Division of Mineral Resources (VDMR) initiated a sampling project to determine chemistry and reflectance (brightness, tint, whiteness) values of Virginia's carbonate rocks. To date, 3963 samples have been collected and 3548 chemically analyzed. Of those analyzed, 128 qualify as high-reflectance material. These results will be published in a series of VDMR reports. These reports will form a database which will provide valuable information to private individuals, companies, consultants, and local and state governments.

INTRODUCTION

Virginia has abundant reserves of carbonate rocks. These rocks range from the high-calcium New Market, Five Oaks, and Rockdell Limestones with as much as 98 percent calcium carbonate ($CaCO_3$) to high-magnesian Shady Dolomite and Honaker Formation containing as much as 45 percent magnesian carbonate ($MgCO_3$) and 53 percent $CaCO_3$. As a result, Virginia's carbonate rocks have potential use for a variety of chemical applications as well as aggregate, which is based on physical properties. During 1987-89, carbonate rocks valued at approximately $80 million per year were produced in Virginia.

This paper focuses on the chemical compositions and chemical uses of Virginia's carbonate rocks. The Virginia Division of Mineral Resources is conducting a study to sample, analyze, and inventory the chemical and reflectance characteristics of these rocks. Determination of the chemical composition and reflectance values identifies formations suitable for various uses. Several major uses are discussed below and several formations are described which meet the requirements for each use.

SAMPLING PROJECT

Between 1845 and 1981, approximately 700 carbonate-rock samples were collected in Virginia and analyzed for chemical composition. In 1981, the Virginia Division of Mineral Resources initiated a project to collect and analyze samples for all carbonate-bearing formations of Virginia. To date, 3963 samples have been collected of which 3548 samples have been chemically analyzed for 10 elements, 147 have been tested for reflectance values, 152 for chlorine content, and 119 have been analyzed for trace elements.

PROCEDURE FOR SAMPLING

An attempt is made to obtain representative samples of each formation in an area. Chip samples as much as 3 inches in diameter are taken across continuous rock outcrops. Samples are taken at 5-foot intervals of true thickness on large outcrops, or closer when needed to sample variations in the lithology. Formations are sampled at approximately 1-mile intervals along strike. Across strike, samples may be taken at closer intervals if folds or faults are present. Impurities such as chert or shale are noted but not sampled.

Sampling continues in an area until the geologist determines sample density is sufficient to give a reasonable representation of each formation.

Initial sampling for this project began in the northern Valley and Ridge province of Virginia. Sampling will continue to progress southward by personnel from the Charlottesville office. Sampling began in southwest Virginia in 1984 and will continue northward by a geologist from the Division of Mineral Resources' Abingdon field office.

Three publications in preparation will report results of analyses for 1) northern Virginia (Winchester and Frederick 0.5°x 1° quadrangles), (Giannini, in prep.,a), 2) north-central Virginia (Front Royal and Washington West 0.5°x 1° quadrangles), (Giannini, in prep.,b), and 3) north-central and central Virginia (Charlottesville and Fredericksburg 0.5°x 1° quadrangles), (Giannini, in prep.,c).

TESTING

Samples are tested in the Division of Mineral Resources laboratory in Charlottesville for 10 elements:

$CaCO_3$	$MgCO_3$	SiO_2	Fe_2O_3	Al_2O_3
K_2O	Na_2O	TiO_2	P_2O_5	S

Samples are crushed until 95 percent passes the 325-mesh and then they are composited; 2 grams are mixed with 2 grams of chromatographic cellulose and pressed into 1.25-inch pellets under 25 tons pressure. Pellets are analyzed using a Diano XRD 700 wavelength dispersive X-ray fluorescence unit. A flow-proportional counter, coarse collimator, and pulse height discriminator are used for all analyses and corrections are made for background levels, dead time, and drift.

To test for reflectance, all samples collected are compared visually to a sample of the same mesh size which is known to reflect 70 percent brightness. Samples which appear to have the same or greater brightness are tested using a Photovolt Corporation reflectance spectrophotometer and a magnesian-carbonate primary standard. The sample is pulverized to 325-mesh size and pressed into a briquette. Brightness percent is determined by reflecting a green filtered light from the briquette. Tint is determined by using brightness percent minus the percent reflection through a blue filter, and whiteness percent is derived by calculations as follows:

Brightness - (Tint X 4) = Whiteness

The testing procedure was adapted from the "Method of Test 5-68T, Determination of Dry Brightness of Ground Limestone", (Pulverized Limestone Association, 1984). To date, 147 samples have qualified as high reflectance material.

CHEMICAL USES

High-purity limestone and dolostone have a variety of uses including: lime production and lime to treat water and sewage, use in the paper and steel industries, and agricultural use to stabilize soil and to enhance its fertility. Environmentally oriented markets include use in control of sulfur and nitrogen emissions from stacks of coal-fired boilers and for acid-control stone. Other markets utilizing high-purity carbonate-rock include fillers and extenders used in fertilizer, animal feed, wallboard joint compound, paint, rug backing, anti-stick agents, the manufacture of chemicals, and rubber.

Five of the highest demand chemical uses are discussed below. These uses include: 1)treating water and sewage, 2)chemical and metallurgical uses, 3)agricultural limestone, 4)fillers and extenders, and 5) control of sulfur emissions from stacks of coal-fired boilers.

WATER AND SEWAGE

The main function of limestone in this category is as the source of quicklime (CaO) or hydrated lime ($Ca(OH)_2$). Treating water and sewage is a major use of lime (Boynton, 1980; Sweet, 1986).

In water treatment, lime is introduced to improve the water quality in several ways. Adding lime will raise the pH level, resulting in reduction of bacteria. At the same time the lime will reduce bicarbonate in the water. Lime will also reduce the suspended solids and turbidity in water. Industries which require large volumes of water use lime to allow the water to be recycled.

Lime is used in sewage treatment to elevate pH levels. This results in precipitation of phosphorian and nitrian compounds and destruction of pathogens.

Generally a high-calcium limestone with 95 percent or greater $CaCO_3$ is required for the manufacture of lime for these applications.

CHEMICAL AND METALLURGICAL USES

Limestone and dolostone and the calcined forms of both have a variety of chemical and metallurgical uses. Their application in the production of glass, paper, or steel are general examples of how the carbonate rocks are used in this category.

High-calcium limestone, high-magnesian dolostone, and lime are used in the manufacture of glass. These materials act as a flux and also make the glass less brittle. Glass made with dolostone has enhanced resistance to quick temperature changes. Chemical requirements for the rock or lime may vary slightly with each producer; however, high-quality glass generally requires 98 percent or greater $CaCO_3$ for limestone and 98 percent or greater $CaCO_3$ + $MgCO_3$ for dolostone. Also Fe_2O_3 generally must be less than 0.05 percent.

Lime is used in the paper industry in several ways. It is combined with chlorine gas to form a stable bleach. This product is then combined with the pulp to bleach the paper. In addition, lime is mixed with sodium carbonate which is a waste product of the paper-making process. It reacts forming sodium hydroxide which can then be reused. Chemical requirements dictate that the limestone source for the lime has 95 percent or greater $CaCO_3$.

Limestone, dolostone, and lime are used as flux in most metallurgical processes. The rock or lime react with the ore to flux out (separate) impurities such as silica, alumina, manganese, phosphorous, or sulfur (Boynton, 1980). Limestone must contain a minimum 95 percent $CaCO_3$ and dolostone should contain a minimum of 95 percent combined $CaCO_3$ + $MgCO_3$ for use as a metallurgical flux. Impurities such as SiO_2 will reduce the ability of the lime to react with impurities in the ore, and therefore should be minimal.

AGRICULTURAL LIMESTONE

Agricultural lime is a general term which can actually refer to pulverized limestone, dolostone or calcined and hydrated lime. The material is spread over soil to regulate the acidity and to introduce the plant nutrients Ca and Mg into the soil. Dolostone actually has a higher acid neutralizing value per unit of weight than limestone.

Virginia state regulations require limestone or dolostone to have a calcium carbonate equivalent [CCE= $\%CaCO_3$ + (1.19 x $\%MgCO_3$)] of 85 percent or greater to be utilized for soil enhancement. Calcined lime must have a CCE of 140 percent and hydrated lime a CCE of 110 percent (Va. Dept. of Agri. and Consumer Services, 1986).

FILLERS AND EXTENDERS

Calcium carbonate has many uses as an industrial filler or extender. It increases body or bulk which reduces costs in making rubber, it adds whiteness and opacity to paint, and is used for loading (filling the voids of paper fiber) and coating paper. In these uses the physical characteristic, brightness, is a main consideration, although limestone used in rubber generally requires 98 percent $CaCO_3$ content. Often, the specific requirements vary from one user to another, but there are industry-wide minimum standards (Boynton, 1980). Generally, a minimum brightness value of 70 percent is required for a material to be considered for use as a filler or extender.

Calcium carbonate is generally preferred over lime (CaO) because the calcium carbonate is more inert to other chemicals in the mixture. The form of the $CaCO_3$ may vary depending on its use; however, it generally is produced as pulverized limestone, whiting (finer, more intensely ground limestone), and precipitated calcium carbonate (produced by chemical processes which result in a uniform, micro-fine, white material).

CONTROL OF SULFUR EMISSIONS

The use of limestone to reduce emission from the stacks of coal-fired plants came into existence with the passage of clean air legislation of the mid-1970's. New clean air legislation, if enacted, will increase demand for limestone usage as sulfur dioxide (SO_2) emissions are restricted to 1980 levels. Five proposed coal-fired power plants to be built in Virginia will require an additional 300,000 tons of limestone annually to reduce SO_2 emissions (personal communication, Alex Glover, 1990).

Two basic methods, scrubbers (or flue-gas desulfurization) and fluidized bed combustors, may use limestone to reduce SO_2 emissions.

In the scrubber method the exhausted gas is sprayed with a limestone medium above the zone of firing. Through a series of chemical reactions, the SO_2 combines with the Ca in the limestone to form $CaSO_4$.

In the fluidized bed combustor method, limestone and coal are introduced onto an air distribution grid in the firing zone. Air forced through the grid creates a suspended bed. Initially oil is introduced into the system to facilitate ignition. After ignition, crushed limestone and coal are continuously fed into the system. The limestone is calcined to CaO, reacts with the SO_2 liberated from the coal, and forms $CaSO_4$ (Sweet and others, 1987).

Experimentation continues on new types of scrubbers and fluidized bed systems. Also, experimentation continues as to the best type of carbonate rocks to use in these methods. Generally the requirements for limestone composition are a minimum 90 percent $CaCO_3$ and a maximum 5 percent $MgCO_3$. In addition to chemical requirements, other rock properties such as permeability are factors in the utilization of limestone in flue gas desulfurization. In 1987, the Division of Mineral Resources conducted a preliminary study of 15 samples from selected quarries and pits in Virginia to determine suitability of selected limestone formations. The New Market Limestone shows greatest potential for this use.

GEOLOGY

Most of the carbonate rocks in the state occur as limestone and dolostone in the Valley and Ridge province of western Virginia. They crop out in long northeast- to southwest-trending valleys between sandstone or siltstone capped ridges. The beds have been folded and faulted and range from flat-lying to vertical and overturned. The limestone and dolostone formations are Cambrian to Mississippian in age with a few, thin limestones of Pennsylvanian age. Potential commercial quantities of high-calcium limestone resources are restricted to Middle and Upper Ordovician age rocks and high-magnesian dolostone reserves are restricted to Cambrian and Ordovician age rocks. In addition to the limestones and dolostones, small Quaternary travertine-marl deposits are present in the Valley and Ridge province.

Minor amounts of carbonate-rock resources are in central and eastern Virginia. Precambrian-age marbles and Triassic limestone and dolostone conglomerates are in the Piedmont province. Tertiary age shell-marl deposits are present in the Coastal Plain.

Several formations that have the greatest economic potential based on purity of rocks and extent of available resources include: the New Market, Five Oaks, and Rockdell Limestones and the Shady Dolomite and Honaker Formation (Figure 1). These formations are described below.

NEW MARKET LIMESTONE

The Middle Ordovician New Market Limestone is in the northern Valley and Ridge province of Virginia. It unconformably overlies the Beekmantown Formation or Rockdale Run Formation of the Beekmantown Group and is conformably overlain by the Lincolnshire Limestone (Figure 1). The New Market is as much as 300 feet thick in Rockingham

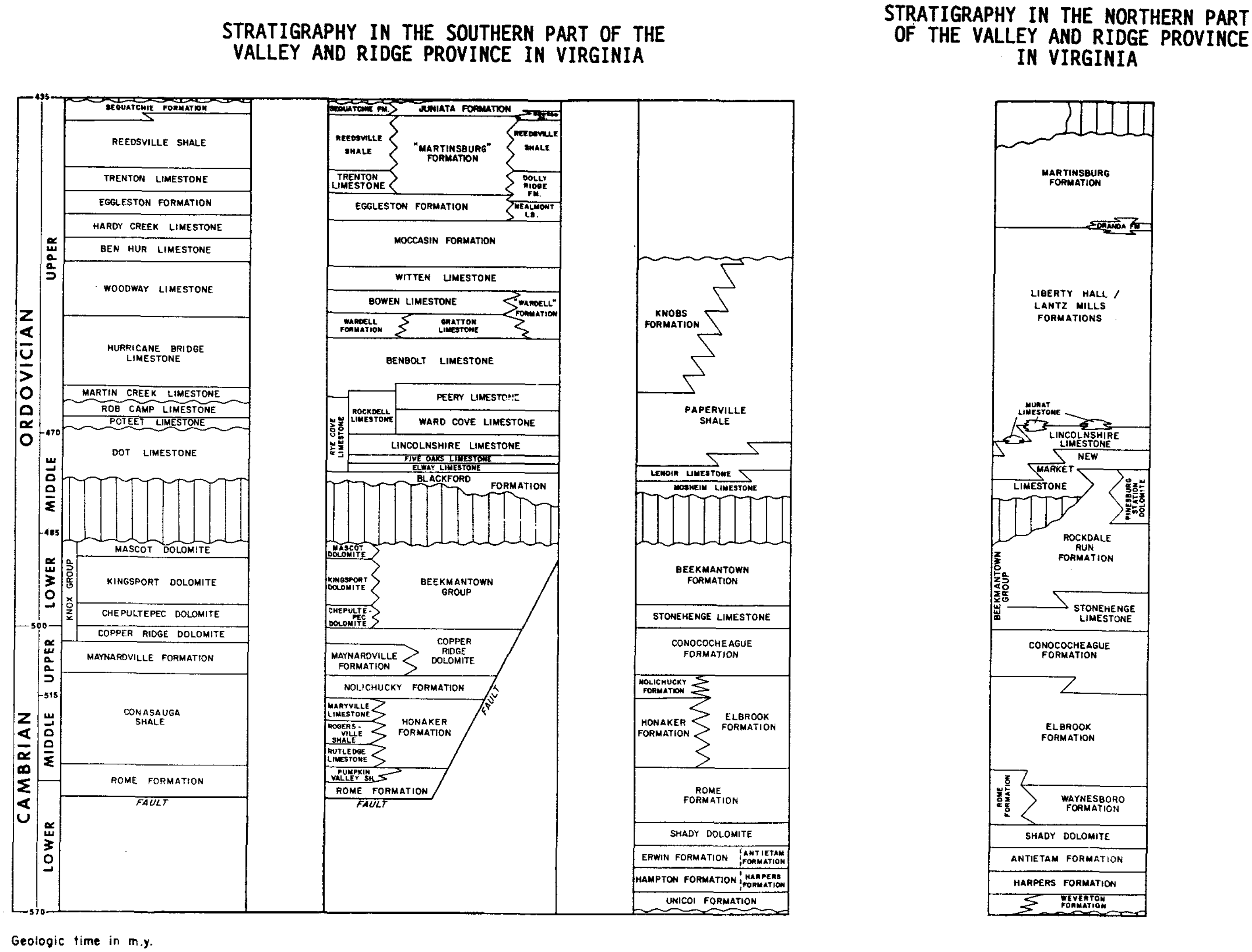

Figure 1. Stratigraphy of the Valley and Ridge province in Virginia (modified from Rader, 1982).

County (Gathright and Frischmann, 1986).

The New Market Limestone can be divided into a lower unit and an upper unit. The lower unit generally consists of carbonate-pebble and -cobble conglomerate at the base that is as much as 75 feet thick. The conglomerate is overlain by a series of thin-bedded, argillaceous, gray, fine-grained limestones containing sparse chert nodules and dolostone.

The upper unit of the formation is the high-calcium "quarry stone". It is a bluish-gray to dove-gray, thick- to massive-bedded, micritic limestone. This upper unit is commonly less than 100 feet thick (Young and Rader, 1974; McGuire, 1970).

Forty four of 53 samples from the New Market Limestone in the area of the Winchester and Frederick quadrangles were limestones. The $CaCO_3$ content of those samples ranges from 88.89 to 99.49 percent, with a mean value of 97.56 percent. In the area of the Front Royal and Washington West quadrangles, 146 of 150 samples taken from the New Market Limestone qualified as limestone. The $CaCO_3$ content of those samples ranges from 78.11 to 99.48 percent with a mean value of 96.96 percent (Giannini, in prep., a,b).

Reflectance values were determined for 43 samples taken from the New Market Limestone. Brightness values ranged from 70 to 88.3 percent (Giannini, in preparation, a,b,c). Present and potential uses for the New Market Limestone include: treatment of water and sewage, in chemical and metallurgical processes, as fillers and extenders, production of agricultural lime, and to control sulfur dioxide emissions from the stacks of coal fired plants. The New Market Limestone is mined by Chemstone Corp. in Shenandoah County, and the Genstar Stone Products Co. and the W.S. Frey Co., Inc. in Frederick Co.

FIVE OAKS LIMESTONE

The Five Oaks Limestone is a Middle Ordovician, high-calcium limestone in the southern part of the Valley and Ridge province of Virginia. It conformably overlies the Elway Limestone and is overlain by the Lincolnshire Limestone (Figure 1). It is well developed in the Tazewell to Giles Counties area. In Tazewell County the Five Oaks is generally less than 45 feet thick, although in one place in northern Tazewell County it measured 117 feet thick. In Giles County the Five Oaks Limestone is as much as 130 feet thick. At Kimballton, Giles County, the upper 40-65 feet is high-calcium limestone (Cooper, 1944).

The Five Oaks Limestone is equivalent to the New Market Limestone of the northern part of the Valley and Ridge province in Virginia. The Five Oaks is generally micritic to fine-grained, dove-gray to dark-gray limestone becoming more argillaceous to the south and containing occasional chert zones. Thirteen samples taken in Russell, Tazewell, and Giles Counties, contained 93.8 to 98.37 percent $CaCO_3$ (Cooper, 1944, 1945). Current and potential uses for the Five Oaks Limestone include: production of quicklime and hydrated lime for water and sewage treatment, production of agricultural lime, use in chemical and metallurgical processes, and use in the control of sulfur emissions from the stacks of coal fired plants. The Five Oaks Limestone is mined in Giles County by APG Lime Corp. and Virginia Lime Co.

ROCKDELL LIMESTONE

The Upper Ordovician Rockdell Limestone is present in Scott and Russell Counties and the southern part of Tazewell County. To the north it is called the Ward Cove and Peery Limestones. The Rockdell conformably overlies the Lincolnshire Limestone and is overlain by the Benbolt Limestone (Figure 1).

The formation ranges from 85-300 feet in thickness and is comprised of several rock types. In some areas the Rockdell is mostly pure high-calcium limestone, in others it is interbedded with dark-bluish-gray limestone or dark-gray, granular, cherty limestone. The high-calcium part is generally light gray to pinkish gray with a coarse-grained texture. Thirty one samples from Russell and Scott Counties have a $CaCO_3$ content of 94.5 to 98.28 percent (Cooper, 1945). Chemical values indicate the Rockdell Limestone could be used in chemical and metallurgical processes, water and sewage treatment, production of agricultural lime, and control of sulfur dioxide emissions from the stacks of coal fired plants. The Rockdell Limestone was recently mined at Speers Ferry in Scott County.

SHADY DOLOMITE

The Lower Cambrian Shady (Tomstown) Dolomite extends the entire length of the Valley and Ridge province in Virginia along the base of the western limb of the Blue Ridge Mountains. It is the oldest carbonate-bearing formation in that area, overlying lower Cambrian sandstones of the Erwin and Antietam Formations and overlain by red and green shale, sandstone, dolostone, and limestone of the Rome and Waynesboro Formations (Figure 1). The Shady Dolomite generally averages 1800 feet thickness except for an anomalously thick section (5000 feet) near Austinville in Wythe County.

The Shady Dolomite is predominantly a high-magnesian unit that is generally fine- to medium-grained, very thick- to massive-bedded, bluish gray to gray and buff to white. In some areas it contains zones of dark-gray to black, very-fine-grained, thin-bedded limestone (Butts, 1940).

Fifteen of 18 samples taken in the area of the Winchester and Frederick quadrangles, were dolostone with 42.54 to 45.11 percent $MgCO_3$ and 51.35 to 56.69 percent $CaCO_3$. In the Front Royal and Washington West quadrangles, 5 of 6 samples were dolostone with 39.98 to 44.63 percent $MgCO_3$ and 50.23 to 53.56 percent $CaCO_3$. Reflectance values for 6 samples taken in the area of the Winchester and Frederick quadrangles range from 70.3 to 83.3 percent brightness (Giannini, in prep, a,b). Current and potential uses of the Shady Dolomite include: chemical and metallurgical processes, production of agricultural limestone, and in fillers and extenders. The Shady Dolomite is being mined in Clarke, Botetourt, and Wythe Counties and the City of Roanoke.

HONAKER FORMATION

The Middle Cambrian Honaker Formation crops out in the southern Valley and Ridge province of Virginia. It overlies shale, sandstone, limestone, and dolostone of the Rome Formation and is capped by shale and dolostone of the Nolichucky Formation. In the extreme southwest the Honaker Formation grades into the Rutledge Limestone, Rogersville Shale, and Maryville Limestone. To the northeast it grades into the Elbrook Dolomite (Figure 1).

The Honaker Formation averages 1300-1400 feet in thickness. It is finely-granular, dark-bluish-gray dolostone with zones of light- to brownish-gray dolostone (Cooper, 1945). Twenty seven of 34 samples taken in Washington County qualify as dolostone with 31.32 to 45.05 percent $MgCO_3$ and 41.96 to 58.97 percent $CaCO_3$. Seventeen of 21 samples taken in Russell and Tazewell Counties qualify as dolostone with 37.08 to 45.94 percent $MgCO_3$ and 52.77 to 57.76 percent $CaCO_3$. Present and potential uses for the Honaker Formation include: chemical and metallurgical processes, fillers and extenders, and agricultural lime. It is quarried in Washington, Scott, and Russell Counties.

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BRICK PRODUCTION, COMBINING ART WITH SCIENCE

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Lawrenceville, Virginia 23868

Brick production involves the processing of clay and shale into a building material that is both durable and aesthetically pleasing in form. At Brick and Tile Corporation, a partly weathered schist and a highly weathered shale and clay residuum are used to produce brick.

Our process starts at the mine site. Successful operation and production of high quality products requires that deposits be located and tested far in advance of actual use. We currently have enough proven reserves to operate at full capacity until the year 2010.

The schist material we use is a fairly hard deposit that has been formed under a great deal of heat and pressure. We utilize a Cat D-8 ripper to loosen up this material and use pans to transport it to stockpiles of up to 100,000 cubic yards. We mine the material in "benches" to blend the material both vertically and horizontally. This material gets progressively harder as we mine deeper. We occasionally encounter some quartz veins in this deposit as well as some sericite. These affect the finished color and are not desirable. We rip up the exposed part of the deposit in the fall and allow the freeze-thaw action in the winter to weather this portion of the material. We can then mine this material, to depths of 30 feet, and place it in stockpiles.

The weathered shale and clay residuum deposit is approximately 10 miles east of the schist deposit at the point where the foothills and coastal plain meet. This shale is fairly soft and layered with a great deal of weathered residuum. We also use the D-8 ripper on this material and pans to transport it to stockpiles. We also mine this material in "benches" for blending purposes. The material is placed in thin layers, which allows a mixture of material from different elevations and areas within the pit and results in uniform properties. We have to be very careful about blending in order to provide a uniform raw material. These piles are approximately 12-15 feet in height and contain from 50,000 to 100,000 cubic yards.

These materials, which are hauled into the plant and stored separately, are currently used in a 1:1 ratio. Approximately 480 tons of material per day, 5 days per/week are ground in hammermills and screened through 6 1/2 mesh screens.

The next step in the process is the forming of the brick. We extrude our brick on two extrusion lines. The ground mix is de-aired in a chamber over the augers before extrusion. An absolute pressure of 2 inches or about 28 inches of vacuum is maintained. This densifies the brick and provides a better quality product. The material is extruded in a continuous column by the augers. A bridge inside of the die forms the core holes continuously. These dies can be made to extrude a variety of shapes. The augers in the machine send two continuous ribbons of clay through the die which must knit back together. Occasionally on some solid brick we may see a small surface defect, which means there are severe laminations inside. We try to make our brick as free of laminations as possible; however the nature of the process is that there are always lamination layers even if you cannot see them. Strange things can also happen if impurities such as carbon get into our material. Carbon must be oxidized carefully during firing for removal or bloating and black coring will occur.

After the brick are extruded they are cut either by real cutters or by push-through cutters and set on kiln cars by hand or machine. During this forming and setting part of the process we must carefully watch the green strength of our ware. This is done by occasionally checking the breaking strength of these green brick. This concern with green strength also requires us to run checks on the particle size distribution of our ground raw material mix. We also vary the mix on small test runs to monitor the properties resulting from the various combinations.

People tend to concentrate their interest on the firing part of the process after they leave the forming area; however, the drying process may be and in fact with us is the more critical area in terms of potential losses. These older plants require about 5,200 BTU's to dry and fire each single brick. The drying portion requires about 3,100 BTU's or about 60% of the total input. The temperature and humidity conditions under which we dry the brick are very critical. We must first run the brick through a predryer that is supplied by heat from the cooling end of the kiln. This energy is applied indirectly to achieve drying at a gradual rate.

The brick leave this area after about 24 hours. They enter a dryer at about 110 degrees F, and 28 hours later they leave dry at 525 degrees F. They then enter the kiln and are heated to about 2000 degrees F. and are then cooled to about 150 degrees F. in 30 hours. We have taken a brick with 20% moisture as 80 degrees F. dried it, heated it to 2000 degrees and cooled it in about 82 hours. They are then either hand unloaded and graded or unloaded by machine.

There is also interest in brick sculpturing wall size murals today. These must be carefully hand crafted by artists and given special care in every step of the drying and firing process to achieve the desired product.

The end result of all of this is a building which has a distinctive appearance with durability and low maintenance.

VARIATIONS IN ROCK PHYSICAL PROPERTIES AS A RESULT OF ENHANCED CEMENTATION: AN EXAMPLE FROM THE SALEM LIMESTONE (MISSISSIPPIAN) OF SOUTH-CENTRAL INDIANA

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ABSTRACT

Pronounced variations in physical properties occur within seemingly similar lithologies of the Salem Limestone (Mississippian), south- central Indiana. The uppermost part of the building-stone facies of the Salem , informally referred to as hard-top stone, is well known among quarriers to be significantly harder to quarry and more difficult to work than the underlying part of the facies. Standard physical tests including absorption, bulk specific gravity, compressive strength, and abrasion resistance in dicate that hard-top stone is denser, stronger, and harder than typical Salem building stone.

Petrographic analyses show that hard-top stone is more tightly cemented with both early-stage overgrowth cement and late-stage neomorphic spar. As the degree of cementation increases, porosity is effectively reduced to decrease absorption and to increase bulk specific gravity. Strength and abrasion resistance also are increased because a greater degree of cementation produces a more lithified and indurated rock.

Enhanced cementation may have been caused as water, saturated in calcium carbonate, migrated down through the hard-top facies from an overlying, more porous facies and promoted further cementation. Similar relationships of more indurated limestone occurring directly beneath a more porous unit also can be documented in the Ste. Genevieve Limestone (Mississippian) of Indiana. Quarry operators who wish to produce a stone with more wear resistance for pavers, stair treads, or for polishing are advised that such hard-top stone has the greatest potential for success.

INTRODUCTION

Pronounced variation in physical properties occur within seemingly similar lithologies in the Salem Limestone (Mississippian) of south-central Indiana. Throughout the Salem dimension-stone district, the upper most part of the building-stone facies is well known among quarriers for being more difficult to saw and mill than the underlying stone. Hard-top stone, the informal name given to this unit, generally requires twice as much time to saw and channel in the quarry as typical dimension stone. Because hard-top stone commonly is too indurated and hard for conventional milling, it is usually scrapped (Patton and Carr, 1982). Some operators, however, have marketed this stone under various tradenames for use as steps and pavers because the stone is more resistant to foot traffic, and at least one company has investigated the possibility of using this material as polished slabs for interior use.

GENERAL GEOLOGY

In a typical Salem building-stone quarry, the hard-top facies averages three to four meters in thickness and constitutes the uppermost part of the building-stone deposits. The contact between hard-top and building stone is difficult to define because both units share the same general characteristics in terms of color, bedding, and lithology. Swarms of stylolites and large solution vugs, however, commonly occur near the center of the hard -top facies and can be used to mark its approximate location (Figure 1). A distinct change in color and lithology marks the upper contact of the hard-top facies with the overlying impure (or "bastard stone") facies. Quarriers generally use this upper contact as a convenient marker to begin benching the stone for quarrying.

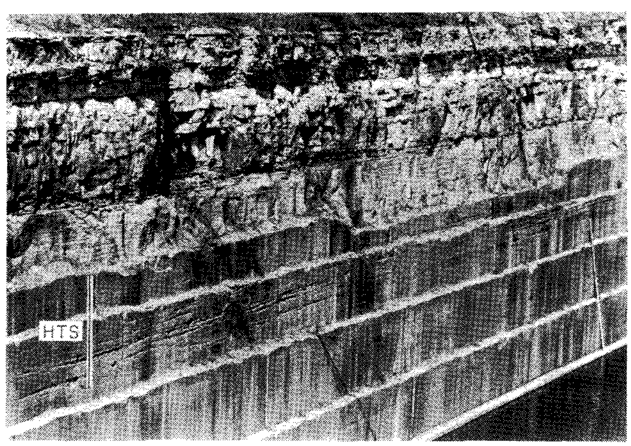

Figure 1. Photograph showing the Salem Limestone in the Empire State Building Quarry, Lawrence County. "HTS" designates the interval of hard-top stone. Note the stylolite swarms and solution cavities. The lower two ledges are each about 11 feet high.

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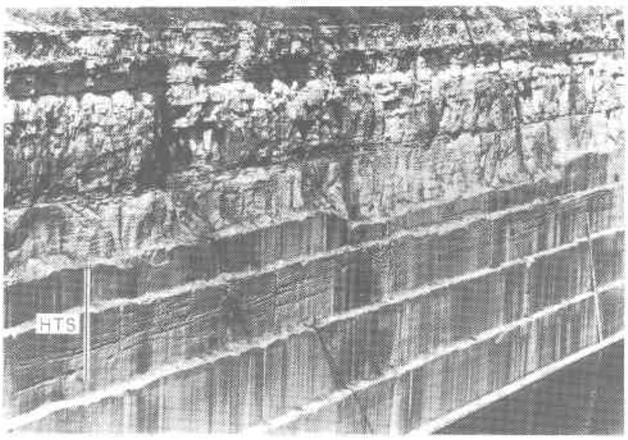

Figure 1. Photograph showing the Salem Limestone in the Empire State Building Quarry, Lawrence County. "HTS" designates the interval of hard-top stone. Note the stylolite swarms and solution cavities. The lower two ledges are each about 11 feet high.

Previous study of the Salem Limestone in the building-stone district near Oolitic indicates that the hard-top facies was deposited under somewhat different conditions than the building-stone facies (Brown, 1987). The building-stone facies is characterized by very thick-bedded deposits of well-sorted and rounded fossiliferous grainstone. Fragments of echinoderms and bryozoans are the dominant skeletal grains (Figure 2). This facies is dominated by thick sets of planar cross-stratification, which suggest deposition in a high-energy system where large quantities of material accumulated to form thick carbonate sand shoals.

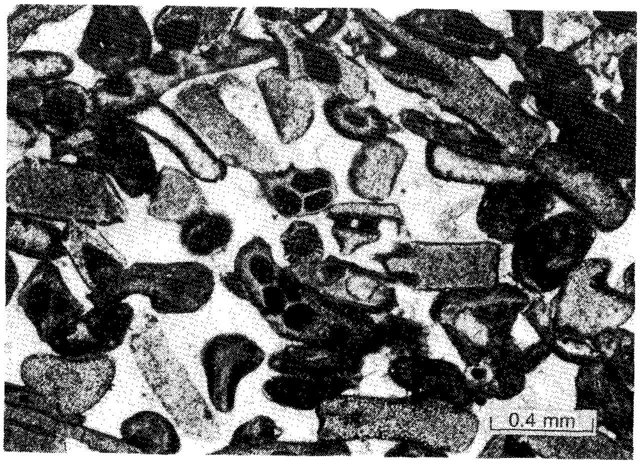

Figure 2. Photomicrograph showing typical building-stone lithology . Note the abundance of well-sorted and rounded echinoderm and bryozoan fragments. Cementation is mainly along grain-to-grain contacts (compare to Fig. 3).

The hard-top facies, also fossiliferous grainstone, was deposited in a sand-flat environment that marked the transition between the shoals and the interior platform lagoon that existed landward of the shoal system (Brown, 1987). The sand-flat deposits contain a distinctive mixture of skeletal grains ranging from echinoderms and bryozoans, which are more common in the shoal deposits, to foraminiferids and calcareous algae, which are most common in the lagoonal deposits (Figure 3). Because the shoals protected the sand-flat setting from normal oceanic swells and currents, sediment transport was minimized. Abundant *Syringopora* coral colonies imply that the sub strate was stable for periods long enough to support colonization by sessile organisms. Many grains have thick distinct micritic envelopes, indicating that the grains were exposed on the surface of the sand flat for considerable periods of time and were micritized extensively before being buried.

PHYSICAL TESTS AND RESULTS

A series of standard physical tests were performed to determine the strength and durability of hard-top stone relative to standard Salem dimension stone. Samples of hard-top and dimension stone were collected from various quarries within the building-stone district (Figure 4). The physical

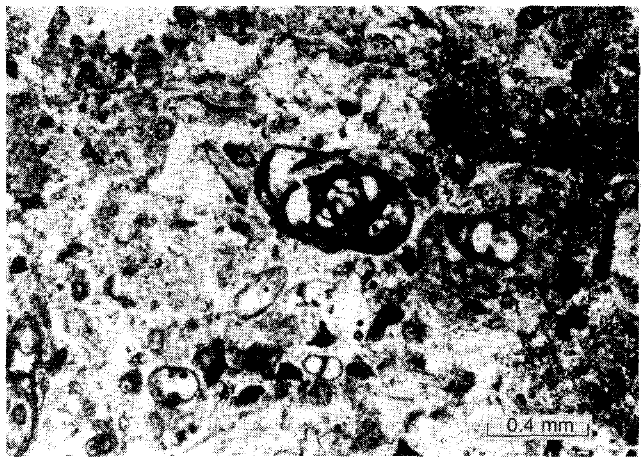

Figure 3. Photomicrograph showing typical hard-top stone. Note the blackened rims produced by micritization on the foraminiferids in the center of the photograph and the abundance of calcite cement.

tests performed include absorption, bulk specific gravity, compressive strength, and abrasion hardness. Triplicate specimens of each test sample were prepared to dimension and tested as specified by the American Society for Testing and Materials (ASTM).

ABSORPTION

Absorption is a measure of the ability of a material to absorb water. Absorption is determined by soaking test samples in distilled water at 20°C for 48 hours then weighing. After drying at 105°C for 24 hours, the samples are weighed again (ASTM C97-83, 1988). The percentage of absorption by weight equals (B-A/A) x 100; A is the weight of the dried specimen and B the weight of the soaked specimen.

The degree to which a material absorbs water can be related to the porosity and permeability of the sample. Decreased values of absorption ideally correspond to decreased porosity and permeability within a sample. Hard-top samples yielded absorption values that are consistently 1 ower than those for the standard samples (Table 1).

BULK SPECIFIC GRAVITY

Bulk specific gravity, or apparent specific gravity, is the ratio of the mass of a sample to that of an equal volume of water at a specific temperature (ASTM C97-83, 1988). Bulk specific gravity is calculated as A/(B- C); A is the weight of the dried specimen, B is the weight of the soaked specimen in air, and C is the weight of the soaked specimen suspended in water.

This test is another convenient method to estimate relative porosity and permeability. Because a material with more pore space per unit volume weighs less than the same material

Previous study of the Salem Limestone in the building-stone district near Oolitic indicates that the hard-top facies was deposited under somewhat different conditions than the building-stone facies (Brown, 1987). The building-stone facies is characterized by very thick-bedded deposits of well-sorted and rounded fossiliferous grainstone. Fragments of echinoderms and bryozoans are the dominant skeletal grains (Figure 2). This facies is dominated by thick sets of planar cross-stratification, which suggest deposition in a high-energy system where large quantities of material accumulated to form thick carbonate sand shoals.

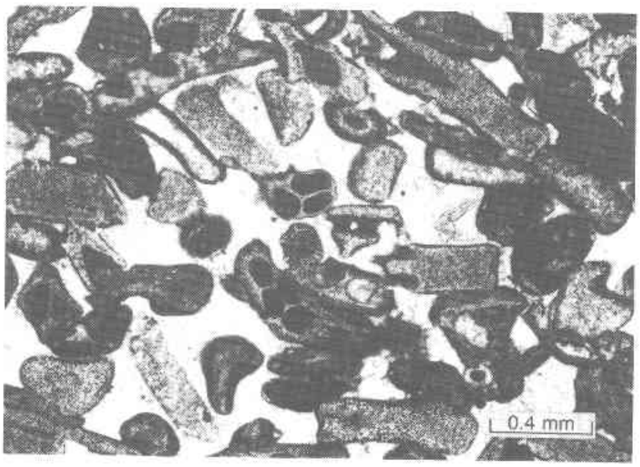

Figure 2. Photomicrograph showing typical building-stone lithology. Note the abundance of well-sorted and rounded echinoderm and bryozoan fragments. Cementation is mainly along grain-to-grain contacts (compare to Fig. 3).

The hard-top facies, also fossiliferous grainstone, was deposited in a sand-flat environment that marked the transition between the shoals and the interior platform lagoon that existed landward of the shoal system (Brown, 1987). The sand-flat deposits contain a distinctive mixture of skeletal grains ranging from echinoderms and bryozoans, which are more common in the shoal deposits, to foraminiferids and calcareous algae, which are most common in the lagoonal deposits (Figure 3). Because the shoals protected the sand-flat setting from normal oceanic swells and currents, sediment transport was minimized. Abundant *Syringopora* coral colonies imply that the sub strate was stable for periods long enough to support colonization by sessile organisms. Many grains have thick distinct micritic envelopes, indicating that the grains were exposed on the surface of the sand flat for considerable periods of time and were micritized extensively before being buried.

PHYSICAL TESTS AND RESULTS

A series of standard physical tests were performed to determine the strength and durability of hard-top stone relative to standard Salem dimension stone. Samples of hard-top and dimension stone were collected from various quarries within the building-stone district (Figure 4). The physical

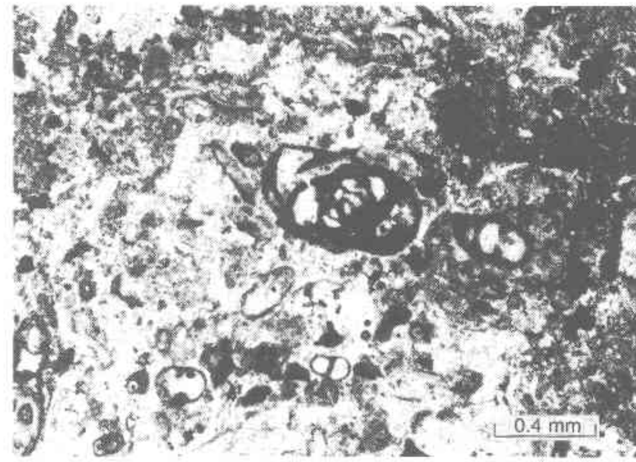

Figure 3. Photomicrograph showing typical hard-top stone. Note the blackened rims produced by micritization on the foraminiferids in the center of the photograph and the abundance of calcite cement.

tests performed include absorption, bulk specific gravity, compressive strength, and abrasion hardness. Triplicate specimens of each test sample were prepared to dimension and tested as specified by the American Society for Testing and Materials (ASTM).

ABSORPTION

Absorption is a measure of the ability of a material to absorb water. Absorption is determined by soaking test samples in distilled water at 20°C for 48 hours then weighing. After drying at 105°C for 24 hours, the samples are weighed again (ASTM C97-83, 1988). The percentage of absorption by weight equals (B-A/A) x 100; A is the weight of the dried specimen and B the weight of the soaked specimen.

The degree to which a material absorbs water can be related to the porosity and permeability of the sample. Decreased values of absorption ideally correspond to decreased porosity and permeability within a sample. Hard-top samples yielded absorption values that are consistently 1 ower than those for the standard samples (Table 1).

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This test is another convenient method to estimate relative porosity and permeability. Because a material with more pore space per unit volume weighs less than the same material

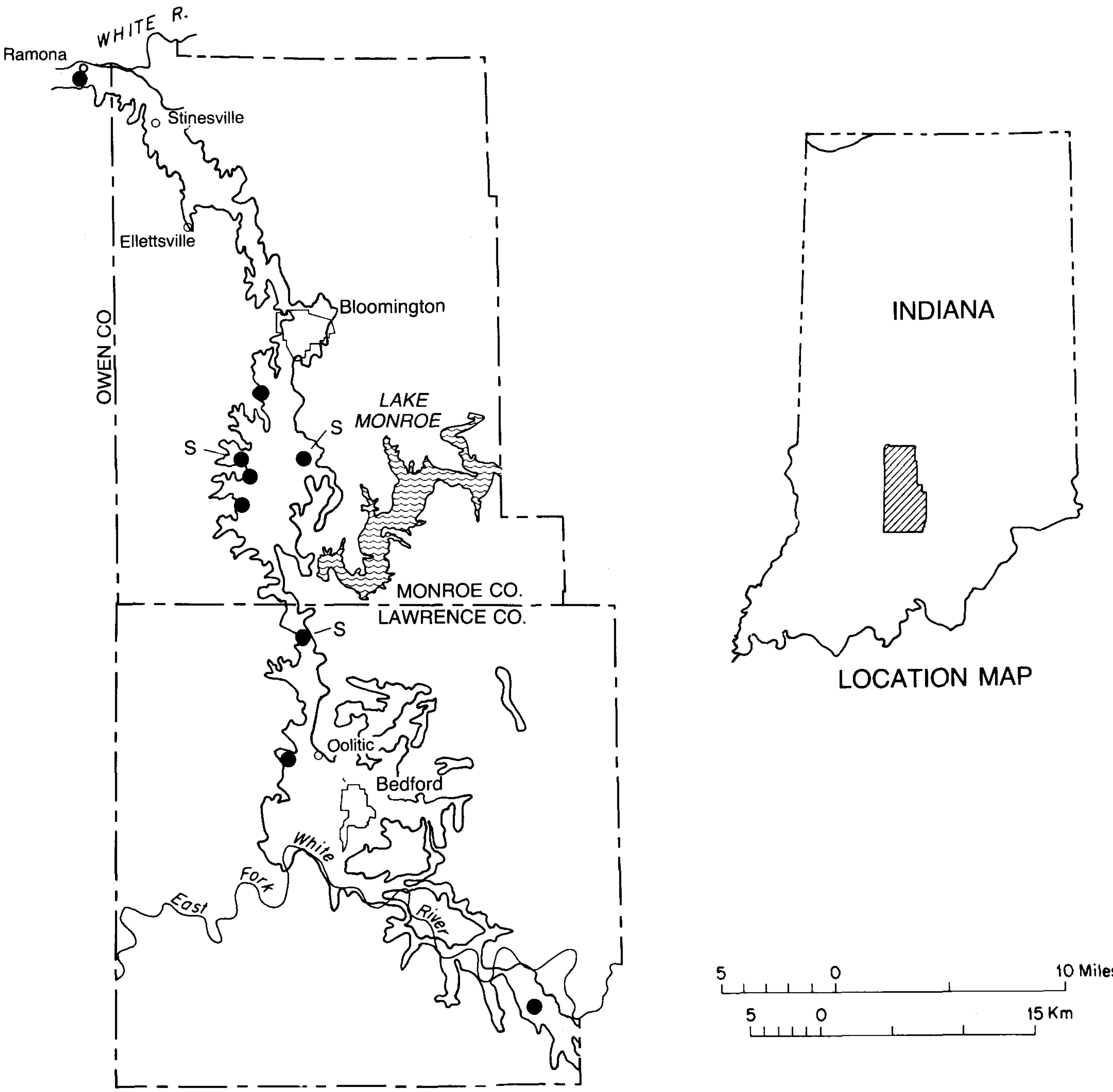


Figure 4. Map of study area showing outcrop of the Salem Limestone and locations of sampling sites for hard-top and standard stone. "S" designations are locations of standard samples.

Table 1. Values of absorption, specific gravity, compressive strength, and abrasion resistance for samples of standard and hard-top stone in the Salem Limestone.

Sample no.	Type of stone	Absorption (percent)	Bulk specific gravity	Compressive strength (lb/sq.in.)	Abrasion hardness
S-1	Standard	5.92	2.22	4,540	6.7
S-2	Standard	5.89	2.23	5,177	6.9
S-3	Standard	5.93	2.21	5,093	6.5
HTS-1	Hard-top	2.54	2.45	14,947	15.5
HTS-2	Hard-top	2.84	2.43	12,709	14.7
HTS-3	Hard-top	4.38	2.33	12,635	11.7
HTS-4	Hard-top	2.31	2.50	13,771	16.2
HTS-5	Hard-top	2.50	2.40	13,041	12.9
HTS-6	Hard-top	1.79	2.57	14,179	25.8
HTS-7	Hard-top	3.48	2.47	10,966	18.1

with less pore space, bulk specific gravity ideally will decrease with increasing porosity and permeability. Hard-top samples yielded values for bulk specific gravity that are consistently higher than those for the standard samples (Table 1). These results agree with the interpretation from the absorption tests that hard-top stone is significantly less porous and permeable than typical dimension stone.

COMPRESSIVE STRENGTH

Compressive strength is the load per unit area that causes a block to fail by shearing or splitting. This parameter is calculated as C = W/A; where C is the compressive strength of the specimen in psi, W is the total load in pounds on the specimen at failure, and A is the calculated area of the load-bearing surface in square inches (ASTM C170-87, 1988). All samples were tested perpendicular to bedding after being dried at 60°C for 48 hours.

In general, values of compressive strength increase with decreasing grain size (Winkler, 1973). Variation in compressive strength also can be related to differences in intergranular bonding. Stone that is weakly cemented or contains a significant amount of pore space (hence less weight per cubic foot) generally fails at a lower compressive strength as compared to a similar material that is more cohesive and indurated. Hard-top stone has much higher values of compressive strength than the standard samples (Table 1), which strongly suggests that hard-top stone is more tightly cemented and indurated than typical dimension stone.

ABRASIVE HARDNESS\

Abrasion hardness is the resistance of a material to abrasive wear. The abrasion hardness value (Ha) is the reciprocal of the volume of material abraded multiplied by ten (ASTM C241-85, 1988). This value is calculated by grinding the samples for 225 revolutions with No. 60 Alundum abrasive under a weight of 2000 grams plus the weight of the specimen: Ha = 10G(200 0+Ws) /2000Wa; where G is the bulk specific gravity of the sample, Ws the average weight of the specimen, and Wa the loss of weight during the grinding operation.

The value of abrasion hardness is dependent on the hardness of individual mineral fragments and the resistance of the mineral bond and bonding agent to tearing. Rocks with a high degree of cementation will resist abrasion more than a similar but less indurated material. Coarse-grained specimens record lower hardness values than denser and fine-grained material because grains loosen more easily along larger interface areas (Winkler, 1973). Abrasion hardness values for hard-top stone are consistently higher as compared to the standard samples (Table 1), which indicates that hard-top stone is much harder and indurated than the standard samples.

DISCUSSION

Results of the physical tests prove that hard-top stone is harder and stronger than conventional Salem building stone. Values obtained from the absorption and bulk specific gravity tests indicate that hard-top stone contains less pore space and therefore, is more dense than standard dimension stone. As a consequence of decreased porosity and increased density, values of compressive strength and abrasive hardness of hard-top stone are substantially greater than those of the dimension stone.

Such marked differences in density, hardness, and strength between the two seemingly identical lithologies can be produced by a difference in grain size or a difference in the degree of cementation. Petrographic analyses of thin sections prepared from each test sample indicate that hard-top stone is composed of skeletal grains that are nearly the same size as standard dimension stone but are more tightly cemented (Figure 5). With an ncrease in cement within the pore spaces, porosity is effectively reduced as indicated by the absorption and bulk specific gravity tests. Strength and hardness are increased because a higher degree of cementation produces a more lithified and indurated stone. Differences in cement type could produce variati ons in strength and hardness, but both materials contain dominant early-stage overgrowth cement.

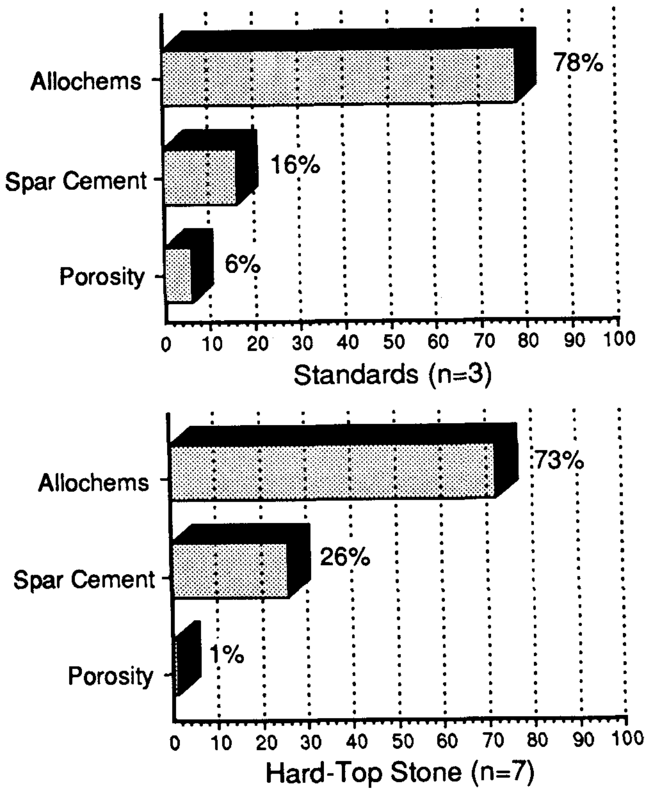


Figure 5. Bar graphs showing point-count data from thin sections of standard and hard-top stone. N equals number of samples studied; 200 point counts were made per sample. Note that the hard-top stonehas more spar cement and less porosity than the standard stone.

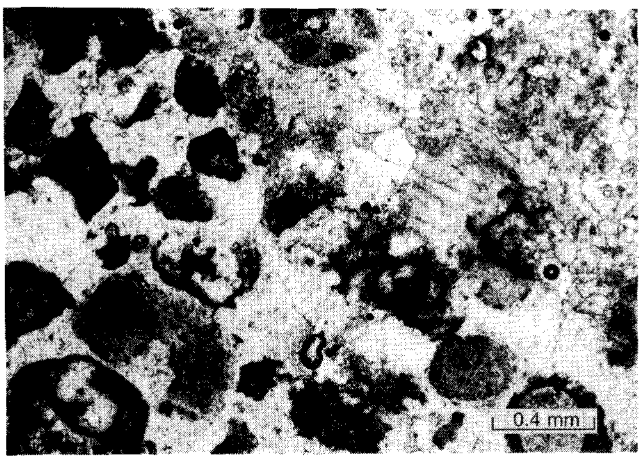


Figure 6. Photomicrograph showing neomorphism in hard-top stone. The foraminiferids in the center of the photograph are partially replaced with sparry calcite. Note the calcite cement, especially upper right, contains abundant inclusions to give the cement a "dirty" appearance.

Some variation in physical properties may be because some of the original grains and early-stage cement within hard-top stone have been transformed to neomorphic spar (pseudospar). This transformation is evidenced by the presence of skeletal grains, especially foraminiferids, that are partially replaced with sparry calcite (Figure 6). These sparry calcite crystals commonly contain relics of micrite or other inclusions that impart a "dirty " appearance to the crystals. This petrographic evidence indicates that some sparry calcite is secondary and developed after the deposition and early-stage cementation of the original grains.

Formation of neomorphic spar is poorly understood but involves an in situ process whereby pre-existing grains and matrix are dissolved on a submicroscopic scale and replaced by new crystals of the same minerals or polymorphs (Folk, 1965). Recrystallization through neomorphism potentially could increase to some degree the compressive strength and abrasion resistance of hard-top stone. As neomorphism proceeds, individual grains and grain-to- cement contacts are transformed into single homogeneous crystals of calcite. Thus, microscopic failure along individual grain-to-cement boundaries is reduced, but the absolute measure of strength that can be attributed solely to development of neomorphic spar can not be determined.

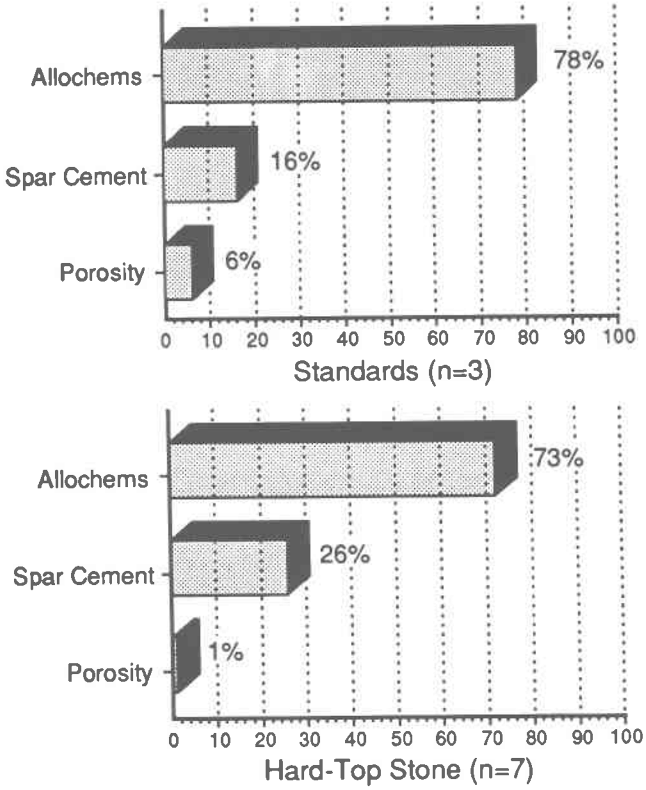
The specific reason why the uppermost portion of the building- stone facies is more tightly cemented and preferentially neomorphosed probably is related more to its stratigraphic position rather than to its depositional history. Cementation and neomorphism require water saturated in calcium carbonate to pass through the sediment to initiate the processes. The "bastard stone" facies that directly overlies the hard-top deposits is highly porous (Table 2) and probably served as a conduit to allow water to migrate easily to the hard-top facies to promote cementation.

A similar example of enhanced cementation can be documented in the Ste. Genevieve Limestone (Mississippian) of Indiana. Carr (1973) found that the absorption values for the top and bottom of an oolite body exposed in a quarry near Orleans, Indiana, were significantly lower than that of the center; a rind of less porous limestone surrounds a core of more porous limestone (Table 3). Directly overlying the oolitic facies is an "impure" highly porous limestone facies, which permitted increased water movement to enhance cementation along the boundaries of the oolite body.

SUMMARY

The uppermost unit of the building-stone facies in the Salem Limestone, informally referred to as hard-top stone, is significantly more in durated and lithified than the underlying and more typical dimension stone. Physical tests, including absorption, bulk specific gravity, compressive strength, and abrasion resistance, indicate that hard-top stone is denser, stronger, and harder than standard Salem dimension stone. Petrographic analyses show that hard-top stone is more tightly cemented by early-stage overgrowth cement and late-stage neomorphic spar, which produces a less porous and more indurated material. Water saturated with calcium carbonate migrated through an overlying, highly porous facies to enhance cementation and to initiate neomorphism.

Because relationships between facies are similar throughout the building- stone district, the hard-top facies should be



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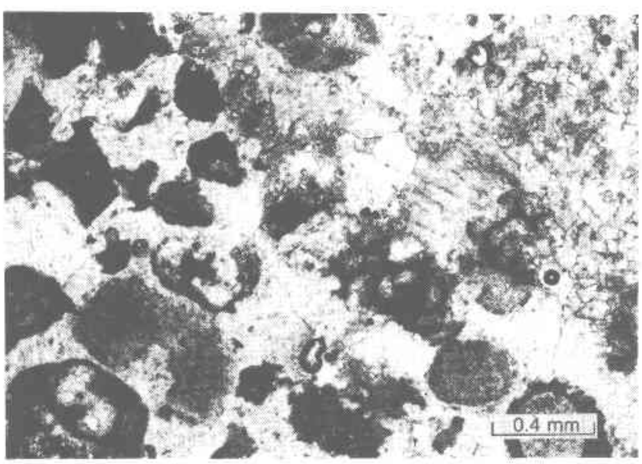

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Because relationships between facies are similar throughout the building- stone district, the hard-top facies should be

Table 2. Average values of absorption and bulk specific gravity and corresponding depositi onal environments of the Salem Limestone.

Quarry terminology	Depositional environment	Description	Absorption (percent)	Bulk specific gravity
Bastard stone	Restricted lagoonal	Limestone, very fine grained packstone/grainstone, well sorted and rounded, dominant grains include peloids and calcispheres.	1.30	2 .56
Bastard stone	Open lagoonal	Dolomite, fine to medium-grained wackestone, poorly sorted, dominant grains include peloids and forams.	8.93	2 .13
Hard-top stone	Sand flat	Limestone, coarse-grained grainstone, moderately to well sorted, dominant grains include forams and echinoderms	2.81	2 .60
Building stone	Shoal	Limestone, medium to coarse-grained grainstone, very well-sorted and rounded, dominant grains include echinoderms, and byrozoans.	5.91	2 .22

Table 3. Average values of absorption and specific gravity and corresponding depositional environments of the Ste. Genevieve oolite body near Orleans (from Carr, 1973, Figure 18).

Lithology	Depositional Environment	Position	Absorption (percent)	Bulk specific gravity
Oolitic limestone	Shoal	Top	1.20	2.64
Oolitic limestone	Shoal	Middle	4.02	2.36
Oolitic limestone	Shoal	Bottom	1.08	2.66

present in most Salem quarries. The thickness of the unit, however, may vary from site to site. Quarry operators who wish to produce a product with high wear resistance for pavers or stair treads or produce a product with potential for polishing are advised that the hard-top stone has the greatest potential for success. Quarriers of any particular stone who wish to market a product with increased durability and hardness but with color and composition that is similar to typical stone may want to investigate the physical properties of the stone occurring near the boundaries with the overlying facies.

ACKNOWLEDGMENT

We thank William H. McDonald, Indiana Limestone Institute of America, Inc., for stimulating discussions of quarrying in general and hard -top stone in particular.

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GEOLOGIC FACTORS AFFECTING THE UNDERGROUND LIMESTONE AND DOLOMITE MINES OF INDIANA

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INTRODUCTION

Limestone and dolomite have been mined underground in Indiana since about 1832, when argillaceous limestone of the Silver Creek Member of the North Vernon Limestone (Devonian) was mined from the north bank of the Ohio River at Clarksville for the production of natural cement. The natural-cement industry in Clark County boomed from the 1860s until about 1900; at least 1 1 underground mines were opened in addition to numerous quarries. Portland cement replaced natural cement for most uses soon after 1900, and as a result all of the mines in the Silver Creek were abandoned by 1909.

Although underground mining of limestone and dolomite never again reached the heyday of the late 1800s, shallow underground mining has assumed greater importance in recent years. Limestone for crushed-stone uses is now produced from three modern underground mines in and near Indianapolis and from one in Crawford County; limestone for glass flux is mined underground in Monroe County; and limestone for dimension stone is mined underground in Lawrence County. The latter is the first underground dimension-stone mine in the state.

The mines at Indianapolis, two drift mines in open-pit quarries and one slope-shaft mine, supply a large metropolitan area with high-quality construction stone in an area where overburden is thick and where surface land suitable for open-pit mining is limited. The active underground mine in Crawford County allows continued mining of limestone at an open-pit quarry where overburden is thick.

As surface use of land in other areas of the state becomes more concentrated, more underground mines will be needed to obtain limestone and dolomite, and the already successful use of underground mining methods to obtain stone for building materials and the chemical industries will encourage further underground mining for these purposes. Therefore, the need to understand geologic factors that influence the mining is also increasing.

GEOLOGIC SETTING

All active and abandoned underground limestone and dolomite mines in Indiana (Figure 1) are at or near the outcrop or subcrop of Silurian , Devonian, or Mississippian rocks (Figure 2) in central, south-central, and southeastern Indiana. These rocks dip westward and southwestward into the Illinois Basin in southwestern Indiana (Gray and others, 1987), where they are overlain by Pennsylvanian rocks that contain limestone strata too thin to be of economic importance.

In most of central and northern Indiana, glacial drift covers Silurian, Devonian, and Mississippian age bedrock to depths that reach more than 400 feet in places. In some restricted areas, such as the Wabash River Valley where drift is thin or missing, open-pit quarrying is possible. In these areas, shallow underground shaft or drift mines also have potential, particularly in stone quarries where surface expansion is limited.

In extreme southeastern Indiana on the Cincinnati Arch, where older rocks are exposed, interbedded thin limestones and shales of the Maquoketa Group (Ordovician) that are unsuitable for commercial development are at the bedrock surface. Nevertheless, potential commercial sources of limestone occur at depth in this area in the underlying Lexington Limestone (Ordovician). The possibilities for underground mining in the Lexington and other deep limestone strata in Indiana were investigated by Carr and Ault (1983), who described the potential for deep high-quality carbonate rock in LaPorte, Vigo, Vanderburgh, and Switzerland Counties, all of which have or are near large populations.

The orientation of joints in underground mines in Indiana directly affects the orientation of rooms and pillars that are needed to support jointed roof rock. Joint patterns in Indiana are consistent with regional patterns in the midwestern United States, which are believed to be related to contemporary stress conditions in the lithosphere (Engelder, 1982). As mapped by Ault (1989) in most of Indiana, primary joints (the most prominent joints) have a preferred east-northeasterly direction, and secondary joints (less prominent) have a north-northwesterly direction.

The prediction of jointing directions has been investigated in open-pit quarries in northern Indiana (Ault, 1988), in two underground limestone and dolomite mines at Indianapolis (Ault and Haumesser, 1990), and in the New Albany Shale (Devonian-Silurian) of southeastern Indiana (Ault, 1990). These studies found that, even though local variations may be present, major joint directions can be predicted to within a few degrees.

GEOLOGIC CONDITIONS AT MINES

CLARK COUNTY

Abandoned natural-cement mines

An argillaceous dolomitic limestone that can be calcined directly into cement without the addition of other raw materials was extracted from the Silver Creek Member of the North Vernon Limestone (Table 1) in underground limestone

Figure 1. Locations of active and abandoned underground limestone and dolomite mines.

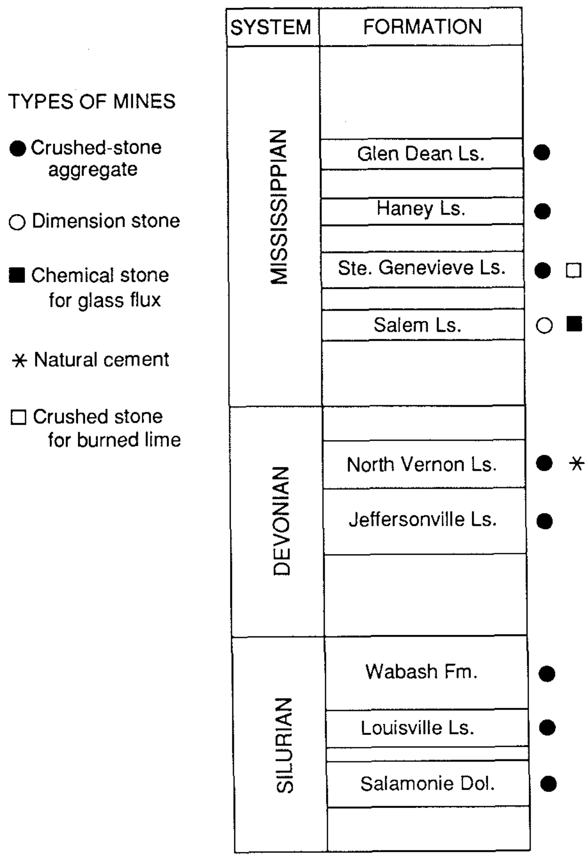


Figure 2. Formations in Indiana mined underground for limestone and dolomite.

mines operated from about 1832 to shortly after 1900. The limestone was mined mostly from open pits, but where the overburden was too thick and too expensive to strip, underground mines were opened into the sides of the pits. The Beechwood Member of the North Vernon, which overlies the Silver Creek Member, is 6 to 8 feet thick, and the New Albany Shale at the bedrock surface above the Beechwood ranges from zero to commonly not more than 10 to 15 feet thick at the mine entrances. Thus, the large Silver Creek mines are extremely shallow in many places.

Siebenthal (1901) reported that rooms 100 feet square were worked. The jointing of the Beechwood and Silver Creek in the large rooms probably contributed to some roof falls, especially considering the small pillars he described. The roofs over large areas of many of the Silver Creek mines are still stable. Surface subsidence has been observed in only one place. Most of the eleven mines in Clark County are flooded or otherwise inaccessible, but limited observations of roof and other mine conditions were possible at the three mines described below.

Silver Creek Cement Co., 900' FNEL X 2200' FNWL Clark Military Grant (CMG) 48

This room-and-pillar mine underlies 50 or more acres immediately west of Silver Creek. The roof rock is about 6 feet of North Vernon Limestone and a variable amount of New Albany Shale that is only a few feet thick in places. No roof collapse is obvious at the adits.

No surface collapse is evident away from the entrances, which suggests that the roof is mostly stable. It has persisted without apparent subsidence for more than 90 years. Although the land over the mine has been used only for agricultural purposes, the capability of the thin roof rock to support buildings is highly suspect and should be carefully considered by anyone involved in the continuing commercial development in the area.

Standard Cement Co., 500' FNWL X 500' FSWL CMG 138

With the exception of small rock fragments that have fallen at the entrance because of weathering, the roof that can now be observed from the entrance of this mine appears quite stable. The present landowners have not observed any falls far into the partially flooded mine, parts of which are now more than 90 years old. The roof is very close to the contact between the Silver Creek and Beechwood Members at a bedding plane that has a pitted and rough surface.

Union Cement and Lime Co., 1500' FNEL X 2600' FSEL CMG 89

Exploration by scuba diving in part of this large partially flooded underground mine (Figure 3) found no major falls, even a long distance from the water-filled quarry where the adits are located (Tom Partipilo, oral communication, 1989). There is, however, an irregular 7-acre area where severe surface subsidence has occurred about 1500 feet southeast of the entrances. Five to 6 feet of North Vernon Limestone and 3 to 10 feet or more of New Albany Shale plus a thin cover of soil have collapsed into the old mine rooms. Sizable trees growing in the subsided area indicate that the collapse occurred many years ago.

Several geologic factors caused or aggravated this collapse including strong jointing in the basal New Albany Shale, which is well exposed in the collapsed pits; joints in the North Vernon Limestone; and large mine rooms poorly supported by small pillars, which were seen in two places where mine rooms that are still open can be entered from the sides of the collapsed pits. Many small pillars are also evident in the mine pattern reflected by the subsided surface. Although not discussed in the literature, miners of that time must have been concerned by the recurring floods of Silver Creek into open quarries and adits. Many of the adits to underground mines that can be located now are partially or fully flooded with ground water.

Until recently, little attention was paid to the obvious danger presented by the old workings that are near or under several small communities north of Jeffersonville. The continued expansion of housing and business developments in the area makes recognition of the extent of the workings in some areas of paramount importance. Many of the mine

Table 1. Underground limestone and dolomite mines in Indiana

County	Clark Military Grant (CMG) or Sec.-Twp.-Rge.	Years of Operation	Remarks
Salamonie Dolomite (Silurian)			
Hamilton	SW1/4 9-17N-4E	1986-present	Active, crushed-stone aggregate
Louisville Limestone and reef facies of Wabash Formation (Silurian)			
Madison	NE1/4NW1/4 28-19N-6E	1972-1981	Abandoned, water-filled
Jeffersonville and North Vernon Limestones (Devonian)			
Marion	NE1/4 33-15N-3E	1985-present	Active, crushed-stone aggregate
Marion	NE1/4 28-15N-3E	1981-present	Active, crushed-stone aggregate
Silver Creek Member of the North Vernon Limestone (Devonian)			
Clark	(Approximate) lat. 38°17'20" long. 85°46'40"	1832?-1884	Abandoned, no trace found
Clark	2000'FNELx800 FSEL CMG 34	1888-between 1900&1906	Abandoned, quarry and mine filled with water and debris
Clark	1400'FNWLx1800' FNEL CMG 36	1869-1893	Abandoned, kiln standing, filled with water and debris
Clark	1000'FNELx100' FSEL CMG 48	1881-1898	Abandoned, kiln standing, mine not accessible
Clark	900'FNELx2200' FNWL CMG 48	1868-1896	Abandoned, dry quarry and open mine adits
Clark	800'FNELx400' FSEL CMG 66	1898-between 1900&1906	Abandoned, partially debris filled quarry at site
Clark	500'FSELx1800' FNEL CMG 66	1866-between 1900&1906	Abandoned, water-filled quarry and mine adits
Clark	2400'FSELx 0'FSWL CMG 67	1898-between 1900&1906	Abandoned, water-filled pit at site
Clark	1000'NWLx2500' FSWL CMG 67	1897-between 1900&1906	Abandoned, quarry and mine partially water filled
Clark	1500'FNELx2600' FSEL CMG 89	1866-between 1900&1906	Abandoned, water-filled quarry and mine adits
Clark	500'FNWLx500' FSWL CMG 138	1897-between 1900&1906	Abandoned, water-filled quarry and mine partially water filled
Jeffersonville Limestone (Devonian)			
Clark	2000'FNWLx2000' FSWL CMG 90	c1960-b1968	Inactive, dry open mine used for storage of explosives
Salem Limestone (Mississippian)			
Lawrence	NE1/4SW1/4 18- 5N-1W	1986-present	Active, dimension stone
Monroe	SE1/4NW1/4 20-10N-2W	1980-present	Active, chemical stone for glass flux
Ste. Genevieve Limestone (Mississippian)			
Crawford	SW1/4NE1/4 15- 2S-2E	a1887-b1903	Abandoned, partially flooded
Crawford	SE1/4SW1/4 6- 2S-2E	1936-1987	Inactive, used for storage and small industry since 1987
Crawford	SW1/4NW1/4 15- 2S-1E	1986	Small exploratory mine, now idle
Harrison	SE1/4SE1/4 10- 2S-2E	a1903-b1953	Abandoned, open and dry
Lawrence	NE1/4SW1/4 12- 3N-2W	c1963	Abandoned, partially water filled
Orange	SE1/4SE1/4 6- 1N-1E	1949-1950	Dry 1-room mine used as maintenance shop
Perry	SE1/4SE1/4 32- 5S-1W	1974-1982	Abandoned, water-filled
Haney Limestone (Mississippian)			
Perry	NW1/4SE1/4 32- 5S-1W	late 1970s-	Abandoned, flooded early 1980s
Glen Dean Limestone (Mississippian)			
Crawford	SE1/4NE1/4 10- 2S-2W	1952-present	Active, crushed-stone aggregate
Perry	SW1/4NE1/4 32- 5S-1W	1974-1981	Inactive, used for storage of explosives

Abbreviations: a-after, b-before, c-about, FNEL-from northeast line, FNWL-from northwest line, FSEL-from southeast line, FSWL-from southwest line locations could be confirmed by shallow drilling, and geophysical methods of locating mine rooms may be effective in some areas.

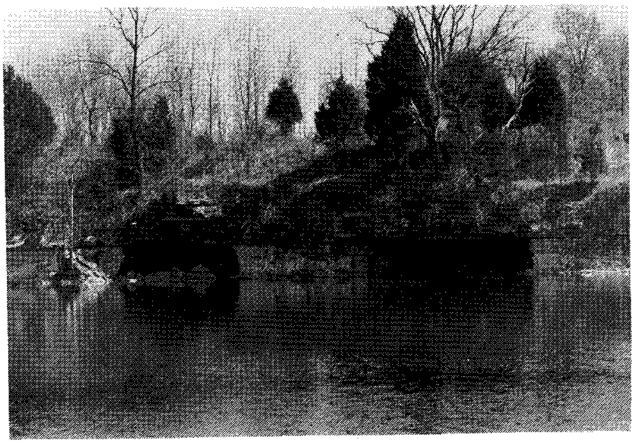


Figure 3. Argillaceous limestone of the Silver Creek Member was extracted for natural cement before 1900 from the Union Cement and Lime Co. mine in Clark Military Grant 89, Clark County. Much of this extremely shallow mine still has a stable roof, but surface subsidence has occurred over one area.

Sellersburg Stone Co. Sellersburg Mine, 2000' FNWL X 2000' FSWL CMG 90

This small abandoned underground mine for crushed stone is at the company's quarry near Sellersburg (Figure 4). Two mine adits 20 feet high by 30 feet wide were opened in the side of an open-pit quarry with the roof at a bedding plane in the Jeffersonville Limestone (Devonian) about 7 f eet below the contact with the Silver Creek Member. A variable thickness of New Albany Shale is at the bedrock surface above the North Vernon. The mine has a very stable roof in the few 30- to 35-foot-square rooms that were excavated. Two pillars about 35 feet square give good support, and jointing is minor. The few joints visible in the roof are at angles to the rooms and entries, which provide further stability to the roof. The Jeffersonville Limestone is fossiliferous and does not appear to have deteriorated in the more than two decades since the mine was abandoned.

CRAWFORD COUNTY

Energy Supply, Inc. Marengo Mine, SE1/4SW1/4 Sec. 6, T 2 S., R . 2 E.

Crushed-stone aggregate was obtained from this mine in the Ste. Genevieve Limestone (Mississippian) that was opened in the side of an open-pit quarry. Rooms and pillars are about 30 to 32 feet high, but they vary in size and pattern over about 110 acres. An additional 14-foot bench was taken from the floor in part of the mine.

Massive micritic and oolitic limestone beds that have prominent bedding planes are exposed in the mine (Carr,

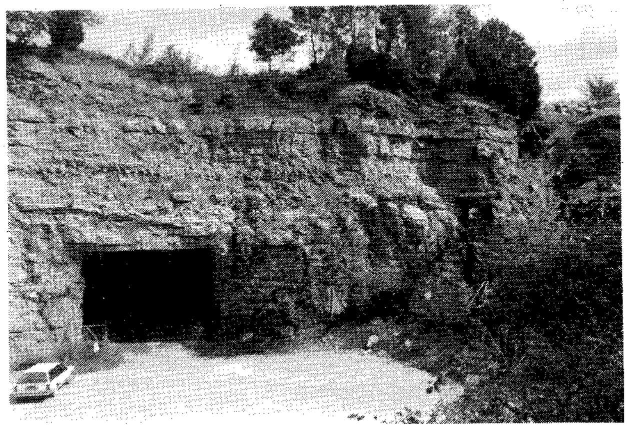


Figure 4. Crushed stone was extracted from this small mine at the Sellersburg Stone Co., Clark Military Grant 90, Clark County. The mine is more than 30 years old. The stable roof is a persistent parting in the Jeffersonville Limestone.

1979). The roof of the mine is a very persistent parting, which imparts a rough but exceptionally stable surface to the roof. Joints are widely spaced for the most part with no apparent fracturing for more than 30 feet in a few places in the 2.5- to 3- foot limestone bed that forms a support beam in the roof of the mine. From the floor of the mine, nearly all of the joints appear tight.

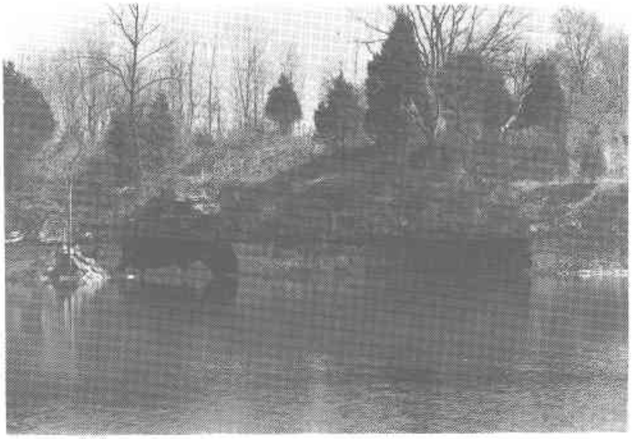
No roof bolts were used. The only fall area is where there are short irregular fractures in beds approximately a foot thick. It is not known whether loose rock from the fractured areas came down at the time of blasting or later. The mine is now clean and has no loose rock on floors to indicate recent falls.

J. B. Speed and Co. Milltown Mine, SW1/4NE1/4 Sec. 15, T. 2 S. , R. 2 E.

Two room-and-pillar limestone mines were operated for many years near Milltown on opposite sides of the Blue River in Harrison and Crawford Counties. The Crawford County mine, on the southwest side, was opened in the Ste. Genevieve Limestone and possibly the upper part of the St. Louis Limestone (Mississippian) to obtain crushed limestone for the production of burned lime. The two adits that could be examined are flooded to within a few feet of the roof, which is at a bedding plane in the Ste. Genevieve. The roof is stable, having no obvious roof falls. This suggests that much of the roof in the old open mine, whose full extent is unknown, may also be stable, because the largest falls in old open abandoned mines are commonly near entrances where temperature and humidity variations are greatest.

Mulzer Crushed Stone, Inc. Temple Mine, SW1/4NW1/4 Sec. 15, T. 2 S., R. 1 E.

A small exploratory drift mine was opened in the lower Ste. Genevieve in the Temple Quarry. The mine, consisting of two adits and a few rooms, has been idle for about three years so that the operator can determine if there are any long-locations could be confirmed by shallow drilling, and geophysical methods of locating mine rooms may be effective in some areas.



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CRAWFORD COUNTY

Energy Supply, Inc. Marengo Mine, SE1/4SW1/4 Sec. 6, T 2 S., R . 2 E.

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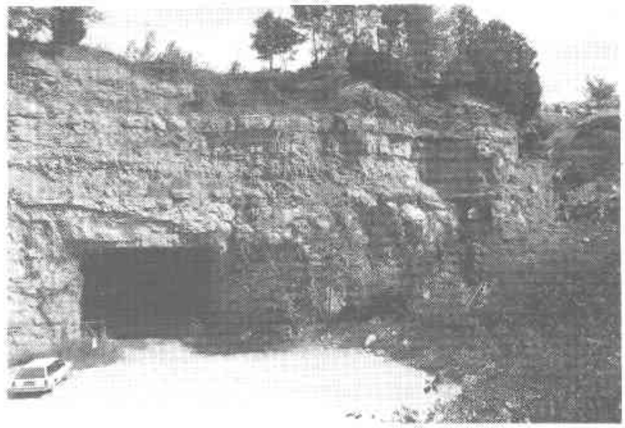

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No roof bolts were used. The only fall area is where there are short irregular fractures in beds approximately a foot thick. It is not known whether loose rock from the fractured areas came down at the time of blasting or later. The mine is now clean and has no loose rock on floors to indicate recent falls.

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Mulzer Crushed Stone, Inc. Temple Mine, SW1/4NW1/4 Sec. 15, T. 2 S., R. 1 E.

A small exploratory drift mine was opened in the lower Ste. Genevieve in the Temple Quarry. The mine, consisting of two adits and a few rooms, has been idle for about three years so that the operator can determine if there are any long-term roof problems. The roof at a prominent bedding plane has held up well with roof bolting only near the entrance of the mine.

Another drift opening was made near the top of the Ste. Genevieve in the same quarry, but thinning of the limestone roof beam and lack of confidence in the stability of the roof as mining progressed prompted the closing of the mine after a short time.

Mulzer Crushed Stone, Inc. Eckerty Mine, SE1/4NE1/4 Sec. 10, T. 2 S., R. 2 W.

About 30 acres have been excavated in this drift mine in the Glen Dean Limestone (Mississippian). The Glen Dean ranges from 18 to 30 feet thick here, and the mine is confined to areas where the formation is thick enough to allow the use of large quarry equipment. The mine is about 22 feet high, generally with large 50-foot pillars and 30-foot rooms. The size of the rooms and pillars are varied to allow customized support of the roof with the pattern of mining oriented at about 45° to orthogonal primary and secondary jointing. Joints are not prominent in the roof rock of this mine, however, and precautionary bolting is used mostly in travelways.

The limestone bed that forms the roof beam of the mine is 2.5 to 3 feet thick, although there is some thinning and lensing of this and other Glen Dean beds, which can cause instability of the roof at their thinned-out edges. The operator uses a "borescope," an instrument inserted into holes drilled into the roof at the centers of intersections, to periodically examine the sides of the hole for open separations between beds.

In a few areas, small irregular patches of roof rock are exposed above the level of the prominent parting used for the roof. No joints or partings are evident in these patches, and the operator believes that shot holes accidentally drilled upward past the roof parting accounts for most of the patches (Kenneth Mulzer, oral communication, 1990).

HAMILTON COUNTY

American Aggregates Corp. 96th Street Mine, SW1/4 Sec. 9, T. 17 N., R 4 E.

Three underground mines in and near Indianapolis yield crushed -stone aggregate from Silurian and Devonian limestones and dolomites. On the north side of the city, aggregate from limestone of the Laurel Member of the Salamonie Dolomite (Silurian) is produced from this room-and-pillar mine. The two adits of the mine are in a quarry face in essentially flat-lying dolomitic limestone of the Laurel, which is fine grained to micritic and massive bedded and which contains some stylolites. The Laurel in the quarry is overlain by about 170 feet of Silurian limestone and dolomite and as much as 3 5 feet of unconsolidated glacial outwash.

The Laurel is mined with little difficulty. The mine is essentially dry, having only a trace of water entering through joints; more water has entered through unplugged drill holes than through natural fractures. The fractures are naturally cemented inpart with calcite, and the danger of roof falls associated with jointing is low. Mine entries and rooms are oriented at angles to the primary and secondary jointing to allow maximum pillar support for jointed rocks.

The clean roof of the mine is at a bedding plane in the Laurel Limestone. Pillars are 35 by 160 feet and have 50-foot intervals. In general, conditions at this mine are excellent, and very few mining problems are associated with geologic hazards.

HARRISON COUNTY

Louisville Cement Co. Milltown Mine, SE1/4SE1/4 Sec. 10, T. 2 S., R. 2 E.

Much of a large rock promontory at this site, on the northeast side of the Blue River, has exposed thick limestone of the Blue River Group (Mississippian) (Figure 5), which has been undermined. The underground mine adits on the west and north sides of the largest of the two quarries in the promontory are 20 to 30 feet wide, and the rooms near the entrances are 25 to 28 feet high in the basal part of the Ste. Genevieve. The pillars in the abandoned mine are arranged roughly in a rectangular pattern but are irregularly spaced from 25 to 60 feet apart in places. Less than 50 percent of the stone was left in the pillars (Baylor, 1932).

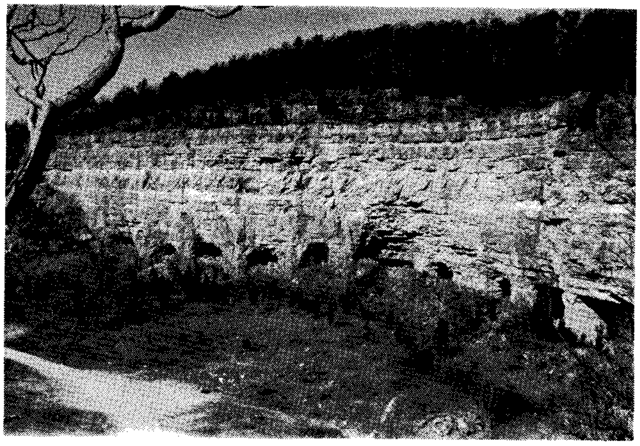

Figure 5. Open adits to the abandoned Louisville Cement Co. crushed-stone mine, SE1/4SE1/4 Sec. 10, T. 2 S., R. 2 E., near Milltown, Harrison County, where burned lime was produced from high-calcium limestone of the Ste. Genevieve Limestone more than 80 years ago.

Near the entrances, where rooms in the mine are well lit and still readily accessible, limestone beds that range in thickness from 1 to more than 3 feet are exposed in the pillars. The limestone is fine grained to micritic and contains abundant fossil fragments. Oolitic zones were reported in the upper part of the mine by Patton (1947), but these are variable in thickness and extent. Near the top of some rooms, beds and fractures that are inclined from about 15° to 45°, possibly partly in deltaic foreset beds, have caused roof instability, resulting in small rock falls.

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HAMILTON COUNTY

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HARRISON COUNTY

Louisville Cement Co. Milltown Mine, SE1/4SE1/4 Sec. 10, T. 2 S., R. 2 E.

Much of a large rock promontory at this site, on the northeast side of the Blue River, has exposed thick limestone of the Blue River Group (Mississippian) (Figure 5), which has been undermined. The underground mine adits on the west and north sides of the largest of the two quarries in the promontory are 20 to 30 feet wide, and the rooms near the entrances are 25 to 28 feet high in the basal part of the Ste. Genevieve. The pillars in the abandoned mine are arranged roughly in a rectangular pattern but are irregularly spaced from 25 to 60 feet apart in places. Less than 50 percent of the stone was left in the pillars (Baylor, 1932).

Figure 5. Open adits to the abandoned Louisville Cement Co. crushed-stone mine, SE1/4SE1/4 Sec. 10, T. 2 S., R. 2 E., near Milltown, Harrison County, where burned lime was produced from high-calcium limestone of the Ste. Genevieve Limestone more than 80 years ago.

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Other falls in an area of the mine that is probably more than 40 years old involve joints that extend down corridors past several pillars. Some falls, bordered in part by joints, have dislodged from the roof at bedding planes from less than one foot to nearly five feet apart vertically (Figure 6), although some falls may have involved several bedding planes at different times. Away from the entrances, the largest falls in the old mine are in areas where the pillars are far apart. Closely spaced joints have caused small falls in at least one area. One large fall of approximately 12 vertical feet at an intersection of corridors is bounded in part by prominent joints.

Figure 6. Roof-fall area near open adits of the abandoned Milltown Mine (see Figure 5). In this photograph, falls from at least five bedding planes in the Ste. Genevieve are bounded by joints oriented nearly parallel to corridors. Also note the small size of the pillar in the foreground.

A large fall of more than 15 feet is exposed at an adit entrance on the southeast side of the promontory. The fall separated from bedding planes in the Ste. Genevieve, and joints border parts of the fall. Here, the mine is directly exposed to the climatic changes of the outside air with fresh-air circulation through this and other nearby connecting adits. The changes in temperature and humidity in the mine are thus particularly severe in this area, which may account in part for the large fall. It should be noted that no roof bolts were used in this mine; roof bolts did not come into common use in coal mines until after World War II (Denver Harper, oral commun ication, 1989), and their widespread use in limestone mines was probably no earlier.

The durability and good condition of many parts of the old mine indicate that if properly spaced and oriented pillars had been used and if roof bolts could have been used when the mine was operating, most of the mine would still be in as good condition as when it was opened.

Because the limestone from the mine was used for burned lime, it was important to the company that the stone be low in magnesium, and chemical analyses of samples of the Ste. Genevieve Limestone at this location by the Indiana Geological Survey shows an average $MgCO_3$ of less than 2 percent where sampled. But the percentage of $MgCO_3$ in limestone varies, and at least part of the reason for the abandonment of the mine, according to Dennis Sarels, a 35-year employee at the mine, was an increase in magnesium in parts of the mine (oral communication, 1970). Mr. Sarels also said that "soapstone" (probably shaly limestone or shale) was encountered and contributed to the decision to close the mine.

LAWRENCE COUNTY

Mitchell Crushed Stone Co. Mitchell Mine, NE1/4SW1/4 Sec. 12, T. 3 N., R. 2 W.

The two adits of this abandoned mine in the Ste. Genevieve are 28 feet high, and the mine is partially flooded. The mine was operated for a short time in 1963 until a large section of the roof about 8 feet thick fell during an idle shift, and the mine was then abandoned. Mr. Lee Powell (oral communication, 1989), superintendent of the operation, believes that thin shale bands in the limestone above the mine were the probable main cause of the fall and made the operation too dangerous to continue. Roof bolts were used extensively in the mine but were ineffective in places according to Mr. Powell. The entrance to the mine, which is heavily bolted, has held up well.

Elliott Stone Co., Inc. Eureka Mine, NE1/4SW1/4 Sec. 18, T 5 N., R. 1 W.

Dimension limestone is mined from the Salem Limestone (Mississ ippian) in an underground room, 80 feet wide and 30 to 35 feet high, in the face of a dimension-stone quarry near Eureka (Figure 7). The rough roof at a prominent parting in the Salem is very stable. Precautionary roof bolting is used routinely. Joints in the Salem at this mine are spaced as far apart as 200 feet. The few joints that were observed at this mine appear to be well cemented for the most part and apparently pose little danger of rock falls. Long rib pillars are used to keep jointed rocks well supported. One side of the mine room excavated thus far is at a prominent joint, giving an irregular side to the dimension-stone blocks removed from that part of the mine.

MADISON COUNTY

Martin Marietta Aggregates Corp. Lapel Mine, NE1/4NW1/4 Sec. 2 8, T. 19 N.,R. 6 E.

Crushed-stone aggregate was produced from this abandoned under ground mine at Lapel. The mine was opened in the north quarry face of an open-pit mine in flat-lying Louisville Limestone (Silurian) at the edge of tilted flank beds of a reef of the Wabash Formation (Silurian). Rooms and pillars are about 40 by 40 feet wide. The rooms are 23 feet high, and a second bench, also 23 feet high, was removed from part of the floor of the mine before it was abandoned. Scaling crews helped clear loose rock from the roof and pillars, but the tilted beds of the reef caused some difficulties in roof control and mining operations where they were encountered (Glen Campfield, oral communications, 1989). The mine is now completely flooded.

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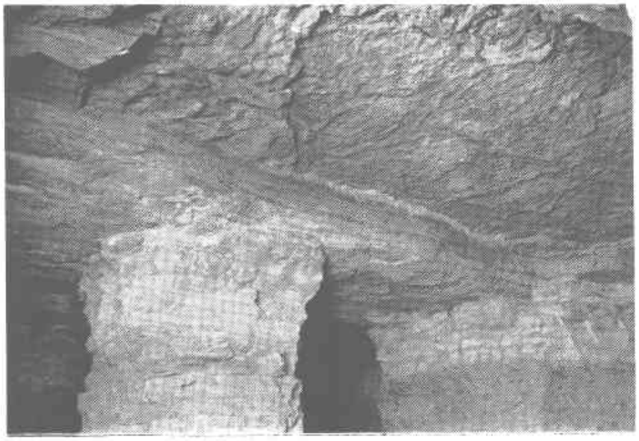

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A large fall of more than 15 feet is exposed at an adit entrance on the southeast side of the promontory. The fall separated from bedding planes in the Ste. Genevieve, and joints border parts of the fall. Here, the mine is directly exposed to the climatic changes of the outside air with fresh-air circulation through this and other nearby connecting adits. The changes in temperature and humidity in the mine are thus particularly severe in this area, which may account in part for the large fall. It should be noted that no roof bolts were used in this mine; roof bolts did not come into common use in coal mines until after World War II (Denver Harper, oral commun ication, 1989), and their widespread use in limestone mines was probably no earlier.

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LAWRENCE COUNTY

Mitchell Crushed Stone Co. Mitchell Mine, NE1/4SW1/4 Sec. 12, T. 3 N., R. 2 W.

The two adits of this abandoned mine in the Ste. Genevieve are 28 feet high, and the mine is partially flooded. The mine was operated for a short time in 1963 until a large section of the roof about 8 feet thick fell during an idle shift, and the mine was then abandoned. Mr. Lee Powell (oral communication, 1989), superintendent of the operation, believes that thin shale bands in the limestone above the mine were the probable main cause of the fall and made the operation too dangerous to continue. Roof bolts were used extensively in the mine but were ineffective in places according to Mr. Powell. The entrance to the mine, which is heavily bolted, has held up well.

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Dimension limestone is mined from the Salem Limestone (Mississ ippian) in an underground room, 80 feet wide and 30 to 35 feet high, in the face of a dimension-stone quarry near Eureka (Figure 7). The rough roof at a prominent parting in the Salem is very stable. Precautionary roof bolting is used routinely. Joints in the Salem at this mine are spaced as far apart as 200 feet. The few joints that were observed at this mine appear to be well cemented for the most part and apparently pose little danger of rock falls. Long rib pillars are used to keep jointed rocks well supported. One side of the mine room excavated thus far is at a prominent joint, giving an irregular side to the dimension-stone blocks removed from that part of the mine.

MADISON COUNTY

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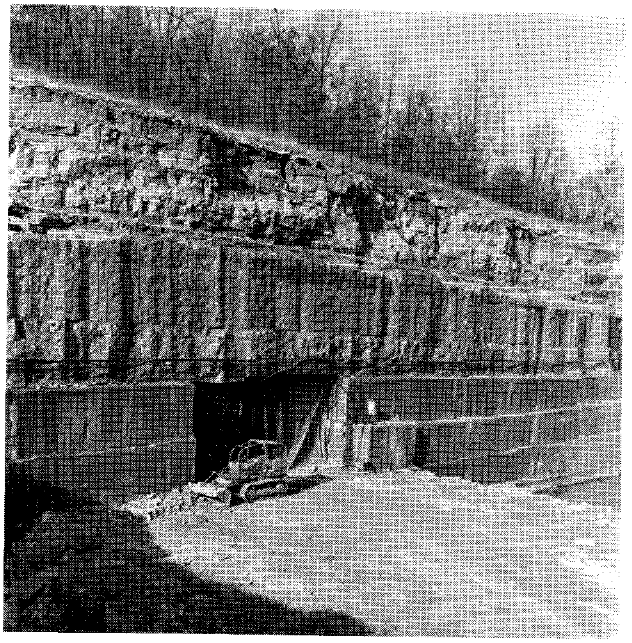

Figure 7. Entrance to the Elliott Stone Co. underground dimension-stone mine at the Eureka Quarry, NE1/4SW1/4 Sec. 18, T. 5 N., R. 1 W., Lawrence County. The underground mine has a stable roof in the Salem Limestone, which exhibits very few joints.

MARION COUNTY

American Aggregates Corp. Harding Street Mine, NE1/4 Sec. 33, T. 15 N., R. 3 E.

In this mine, opened in a quarry face on the southwest side of Indianapolis, fine-grained to micritic Jeffersonville and North Vernon Limestones are extracted to obtain high-quality aggregate without stripping the overlying thick shale and unconsolidated overburden (Ault and Haumesser, 1990). About 8 feet of North Vernon Limestone constitutes the roof of the mine, which supports 50 to 60 feet of New Albany Shale. The height of the mine is approximately 24 feet, which includes about 19 feet of North Vernon Limestone and 4 to 5 feet of Jeffersonville Limestone.

The clean roof of the mine is at a thin shale parting in the nearly flat- lying North Vernon Limestone. Originally, the orientation of the entries was about 20 degrees to the primary jointing, but a roof fall occurred in off- shift hours at a joint swarm (closely spaced joints) where some of the jointed rocks were unsupported for more than 200 feet. The apparent spreading of joints discovered on a routine inspection gave advance warning of the danger. The present orientation of the mine, changed from the original mine plan, is to allow support of jointed rocks in short distances, in this mine about 87 feet. An ongoing program of joint mapping in the mine allows the company to outline areas that have a greater potential for roof falls. The company avoids placing intersections of entries in such trends.

Present mining is with 35 by 160 foot pillars that are about 40 feet apart. Eventually, additional parts of the oversized pillars will be selectively removed to obtain additional reserves while leaving strategically placed pillars to support the roof.

As in the company's 96th Street Mine, water influx is minor. Many joints are sealed with calcite or tarry petroleum coatings derived from the overlying New Albany Shale (Devonian-Mississippian).

Martin Marietta Aggregates Kentucky Avenue Mine, NE1/4 Sec. 28, T. 15 N., R. 3 E.

The Kentucky Avenue Mine on the south side of Indianapolis is about 1 mile north of American Aggregates Harding Street Mine, so close that blasting in one mine can sometimes be felt in the other. A slope shaft to a depth of about 140 feet provides access to the 100-acre mine, which has rooms and pillars that are both approximately 40 by 40 feet wide, resulting in about 75 percent recovery of the limestone for high-quality crushed-stone aggregate. About 6 feet of Jeffersonville and 17 feet of North Vernon are exposed in 23-foot high rooms. About 46 feet of the Jeffersonville and North Vernon Limestones are exposed where a second bench has been removed from the floor in part of the mine.

Original plans for the mine called for entries that were oriented north- south and east-west. Early mining exposure of jointing systems oriented in nearly the same direction caused the company to change the direction of the mine entries to nearly northeast and northwest to provide better support for jointed roof rocks.

The spacing of the primary east-northeastward-trending primary joints in the mine range from inches to 20 feet or more apart. Petroleum residues from oil shale of the New Albany, which is more than 50 feet thick in a few places above the North Vernon, coat the sides of some pillars and patches on roof surfaces in a few places. No water was seen entering the mine from coated joints, which are partially or completely sealed by the residues. Minor amounts of water enter through some uncoated joints.

Most of the mine has an unbroken roof at an extensive thin shale band in the North Vernon. The stable surface of much of the roof is rough, exhibiting small ridges and pits mostly less than an inch in height and a few inches in length. Roof bolting is generally effective, although some close and repeated bolting is necessary in areas where the joints are closely spaced (swarms).

A number of joint swarms have been encountered. They trend at angles of about 45° to the pillars. In some areas, danger from loose rock, especially from anastomosing joints in the swarms, is reduced by spacing roof bolts closely, scaling freshly shot surfaces with particular care, and rescaling after a period of time if necessary. Loose triangular splinters of limestone that are less than a foot to little more than a foot in thickness and that are bounded on at least one side by a joint surface are common at the swarms. Where joints are farther apart, thin slabby blocks bounded by joints can be seen in a few places.

To avoid any delayed small rock falls, freshly mined swarm are as are left idle for a time after first shooting and

Figure 7. Entrance to the Elliott Stone Co. underground dimension-stone mine at the Eureka Quarry, NE1/4SW1/4 Sec. 18, T. 5 N., R. 1 W., Lawrence County. The underground mine has a stable roof in the Salem Limestone, which exhibits very few joints.

MARION COUNTY

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To avoid any delayed small rock falls, freshly mined swarm are as are left idle for a time after first shooting and bolting. As in the American Aggregates mine a short distance southward, the swarms tend to stay on trend with the major joint directions, but the extent of individual swarms along trend is unpredictable. But the prediction of the direction of the swarms, if not their extent, allows extra caution to be taken along the swarm trends as mining proceeds.

Fein (1983) indicated that blast damage in the roof rock was also the cause of roof falls in this mine, particularly where the roof sloped in the direction of mining.

MONROE COUNTY

Hoosier Calcium Corp. Gosport Mine, SE1/4NW1/4 Sec. 20, T. 10 N., R. 2 W.

High-calcium limestone crushed for glass flux is produced from an underground mine in the Salem Limestone near Gosport. The mine occupies about 12 acres with rooms 45 to 50 feet wide and pillars 50 to 55 feet square. The rooms, which are mined in a roughly rectangular pattern oriented east-west, are 25 to 30 feet high, and a small part of the mine has a floor bench removed to a depth of about 12 feet.

The roof of the mine is at or near the contact between the fine- to medium-grained Salem Limestone and the overlying fine-grained to nearly micritic St. Louis Limestone. Although much of the mine roof appears stable at a parting in the Salem, fractures and inclined bedding in the upper beds of the Salem and in the basal St. Louis have caused roof problems in parts of the mine. The fractures appear to trend nearly east-west in part but are irregular and allow some unstable roof conditions, particularly at the thinned-out edges of some inclined beds. Roof bolting has been used only at the mine entrance thus far.

ORANGE COUNTY

Calcar Quarries, Inc. Paoli Mine, SE1/4SE1/4 Sec. 6, T. 1 N., R. 1 E.

At this operation near Paoli, a one-room underground mine in the Ste. Genevieve Limestone is used as a shop for servicing equipment for the quarry operation. The roof at a prominent bedding plane has been bolted and appears stable.

PERRY COUNTY

Mulzer Crushed Stone, Inc. Derby Mine, SE1/4SE1/4 Sec. 32, T. 5 S., R. 1 W.

About 5 acres of the upper part of the Ste. Genevieve Limestone was mined here for crushed-stone aggregate. Thin shale partings in the roof rock caused some roof falls and the need for closely spaced roof bolts. Corrosion of the roof bolts by seeps of acidic water was also a problem (Kenneth Mulzer, oral communication, 1990).

Mulzer Crushed Stone, Inc. Derby Mine, NW1/4SE1/4 Sec. 32, T. 5 S., R. 1 W.

A room-and-pillar mine of about 5 acres was operated here for about 4 years in the Haney Limestone (Mississippian). The Haney contains thin limestone beds and shaly partings, which required roof bolts for roof control during much of the operation of the mine. Mining in other stratigraphic positions in the Haney was attempted, but the need for roof bolts made the operations overly expensive for crushed stone.

Conex, Inc. Derby Mine, SW1/4NE1/4 Sec 32, T. 5 S., R. 1 W.

This 25-acre drift mine in the Glen Dean Limestone was originally operated by Mulzer Crushed Stone for crushed-stone aggregate. Rooms are about 20 feet high near the entrance, and rooms and pillars vary in width, some being more than 30 feet long. Extra large pillars were left routinely. Where observed in the mine, jointing is widely spaced and only slightly developed. No roof falls are associated with jointing that was examined near the entrance. Rooms and pillars are oriented at about 40° to 45° to what little jointing is present.

Roof bolting near the entrance was used to help control a thin limestone bed that ranges from less than 2 inches to nearly a foot thick and which has remained securely in place since shortly after the mine was opened . The overlying limestone bed forming most of the roof in the mine still appears quite stable over a large area near the entrance. Kenneth Mulzer (oral communication, 1990) reported that the roof rock deeper in the mine was also stable during active operations.

The Glen Dean Limestone does not maintain a consistent thickness, and usable reserves were limited. The necessity for use of large quarry equipment in the Glen Dean presented problems with a shaly floor and a thin limestone roof in places. These were the main factors that caused the company to stop underground crushed-stone operations.

Conex, Inc. now uses a few rooms near the front of the mine to store explosives and equipment.

DISCUSSION

Rooney and Carr (1971) discussed the advantages and disadvantages of mining industrial limestone underground including the advantage of selective mining to obtain particular beds. This is a major factor for all of the active mines in Indiana as it was for most of the abandoned mines. Near Indianapolis, sources of limestone and dolomite for high-quality crushed-stone aggregate are either overlain by carbonate rock of lesser quality or are overlain by thick shale and unconsolidated overburden, which are the main reasons the three active underground mines at Indianapolis were opened. Protection from the weather and confinement of environmental problems underground are lesser factors that make the operations of these mines attractive.

The two active underground mines in the Salem Limestone, Elliott Stone's dimension-stone mine in Lawrence County and Hoosier Calcium's flux stone mine in Monroe County, were opened to exploit the Salem's distinctive qualities as a source of dimension stone and for its chemical purity for glass flux. Other important factors contributing to the decisions to open the mines were the ability to mine dimension stone throughout the year, the presence of thick overburden at one location (Figure 7), and the ability to mine chemically pure fluxstone without surface contamination. Two geologic factors are by far the most important for the safe and economic design of the shallow mines. Bed thicknesses and jointing conditions in the roof rock determine the stability of the roof and the potential for roof falls, which is the single most hazardous and expensive problem that can occur in an underground limestone mine. If mine design and mine operations take these conditions into account, underground mining of shallow carbonate rock in Indiana can be highly successful. These factors are of great importance in all of the formations that were or are mined in Indiana. The softest rock mined is probably the Salem Limestone, and jointing and bedding are as important in this formation as in the hard and brittle fine -grained to micritic beds of other formations.

In all of the mines that could be examined, primary jointing directions are generally east-northeasterly and secondary joints are north-northwesterly, following regional patterns. Where the primary joints are far apart (20 feet or more) and well cemented, roof conditions are excellent and small falls are rare. Commonly, no roof bolting is necessary under these conditions. Where joints are close together, particularly in swarms (inches to less than about two feet apart), roof falls are a distinct possibility, and precautions are needed. Roof bolting is necessary in most places where swarms occur, but even roof bolting is not always or everywhere successful.

Additional precautions that may help control roof conditions where swarms are present include:
1) orienting the mine at acute angles to the orthogonal jointing to give maximum support to jointed rocks in short distances (as opposed to having prominent jointing parallel to and along corridors),
2) allowing closely jointed rocks to set for a sufficient period of time to allow for small falls that may occur immediately after mining, then rescaling and rebolting,
3) leaving long pillars under and completely across swarm trends or keeping long rib pillars entirely under swarms (not easily accomplished because the length of swarms are difficult to predict),
4) and keeping entry intersections away from the swarm trends as much as possible.

In some of the old abandoned mines, even where jointing is widely spaced and mostly tightly cemented, roof falls bounded by joints occur where primary jointing runs down long corridors past several pillars. Poor roof conditions are exacerbated in the mines where pillars are small.

The second of the two most important geologic factors, thin bedding in the roof rock, caused the closure of at least one underground operation and probably was a contributing factor in the closing of others. The carbonate roof beam, the lowermost bed that forms the roof of the mine, is at least 2.5 to 3 feet thick in all of Indiana mines with stable roofs. Because all of the mines in Indiana are less than 200 feet from the bedrock surface and most are less than 100 feet, the strength of the roof beams for these shallow mines may not be sufficient for deeper mines. No durability or strength tests were performed in this study.

Some bedding separations are at thin shale laminations or at stylolites; other separations appear to be cemented by calcite to the bed above. It was not determined what effect different conditions at bedding separations have on roof stability, but intuitively it would seem that the tighter the bond between beds the better.

Limestone and dolomite roof beds that thin over the large areas of some mines present a hazard that may not be easily detected. The thin edges of such beds make for an unstable roof that may require roof bolting. As mentioned above, one operator, Mulzer Crushed Stone, looks for thin roof beds and open separations between beds by drilling holes into the roof at mine intersections and by using an optical instrument to examine the sides of the hole.

Some roof falls in abandoned mines involve both thin beds and poorly supported jointed rocks. This was particularly noticeable at the abandoned Milltown Mine in Harrison County. Here at least one and probably several falls occurred at the same place in the mine at separations between thin beds that occur on top of each other. Some falls are also bounded by joints in rocks that are not supported for long distances by pillars. An additional cause for some of the falls, mentioned above in the mine descriptions, may be the varying temperatures and humidities that occur in old open mines. Roof bolting would undoubtedly have prevented many falls.

Inclined bedding and fracturing within essentially flat-lying beds, especially where such beds are at or near the roof of a mine, may allow small falls, and such beds may not be detected until the mine has been opened. If possible, the mine roof should be raised or lowered to other partings to help control falls.

Facies changes, particularly where clay content or shale increases in a limestone mine, are obviously unfavorable. So are increases in magnesium in mines that are being used as a source of high-calcium limestone. Color changes, textural changes, or an increase in the number of stylolites in a dimension-stone mine are also detrimental. Here again, a closely controlled exploratory drilling program can detect many of these conditions before mining starts.

The underground mining of Silurian reef rock, present in a small part of the abandoned underground mine at Lapel, Madison County, has not been attempted elsewhere in Indiana, although much high-quality reef rock is quarried from open pits in north-central Indiana. The steeply tilted flank beds in the generally dome-shaped reefs present operational mining problems that will have to be overcome to make underground mining practical in the reefs.

As far as is known, water influx into the shallow Indiana mines has not been much of a problem. Small amounts enter some mines through open joints, but many joints are cemented by calcite or, in the case of mines in limestone beneath the New Albany oil shale, sealed with petroleum residues.

Because many of the underground mines in Indiana are so shallow, the danger of surface subsidence would appear to be great. Surprisingly, it was found that nearly all of the mines in Indiana, active or abandoned, are stable for the most part with surface subsidence caused by hazardous geologic conditions occurring in only a few places. It was also apparent that even where mines had been abandoned for many years and some roof falls had occurred, the worst falls had worked up through not more than 10 to 15 feet of carbonate rock. This speaks well for the stability of the old mines and for the environmental safety of active and future mines.

In the most extensive area of surface subsidence known (approximately 7 acres in Clark County), a pre-1900 mine is in extremely shallow bedrock, probably less thick than the height of the mine itself. Other old mines in this area may be at similar shallow depths, and where these conditions are present, surface subsidence is still a hazard.

CONCLUSIONS

Most of the 28 underground limestone and dolomite mines in Indiana were opened to exploit particular beds as an alternative for open-pit mining where removal of thick overburden is economically prohibitive or where overlying materials are marketed more slowly than the materials mined underground. Other, but less significant reasons, include year-round production because of protection from adverse weather conditions, confinement of undesirable environmental conditions underground, and protection of chemical stone from surface contamination.

Generally, the mines have or have had good operating conditions with mostly stable roofs, many of which do not require roof bolting. There is very little water influx in active mines, and all except a few extremely shallow abandoned mines have long-term resistance to surface subsidence. Careful planning of mine design and mine operations further enhance the safe and economic operations of the active mines.

The two most important geologic factors that have affected the mines are jointing and bedding conditions in the roof rock. Jointing orientation and spacing and bed thickness in carbonate roof rock determine in large part the stability of the roof, the need for roof bolting, and the likelihood of surface subsidence in extremely shallow mines. Other factors that affect the mines include variable thicknesses of roof beds resulting in very thin or feather-edge roof beams in parts of some mines; overall thinning of some minable rock units limiting minable reserves; inclined bedding and fracturing in some rock units; facies changes, particularly increases of magnesium content in high-calcium limestone mines and increases in clay or shale in other mines; and steeply tilted flank beds in reef rock.

Some effective measures that can be taken to anticipate and reduce hazards in shallow mines in Indiana include sufficient exploratory and development test drilling, orientation of mines to support unstable roof rock, strategic placement of large pillars to help support jointed rocks, and roof bolting in hazardous areas.

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PATTERNS OF FLUORINE DISTRIBUTION IN NEOGENE PHOSPHORITE MACROGRAINS, AURORA DISTRICT, NORTH CAROLINA

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ABSTRACT

Pelletal, skeletal, and intraclast macrograins have been analyzed for fluorine (F), phosphorus (P) and other elements from phosphorites in the Neogene Pungo River and Lower Yorktown Formations in the Aurora Phosphate District, North Carolina. Fluorine analyses display a broad range of values, and as F content shows a positive correlation with CO_2 in apatites, this suggests that CO_3 and F or the CO_3/F group substitute for PO_4 in the apatite structure.

Fluorine values increase consistently from core to margin within pelletal macrograins of carbonate facies units. We believe such distributions result from fluorine absorption of pore fluids during diagenesis. No consistent patterns of fluorine distribution have been observed in either terrigenous facies or skeletal and intraclast macrograins, nor has any discernable relationship been observed to date between the depths (ages) of the phosphate horizons and the F/P_2O_5. We conclude that fluorine accumulation has yielded the resultant carbonate fluorapatite grains sufficiently resistant, both mechanically and chemically, so as to survive reworking and permit accumulation.

INTRODUCTION

The purpose of this study is to document the addition of fluorine to apatite-rich macrograins, the primary constituent of phosphorite deposits, during formation. We believe we can show that fluorine is consistently added to pelletal macrograins during diagenesis and may also be added to the other two types, although subsequently removed during weathering.

Recent studies on this topic have shown that 1) the evolution of modern phosphorite nodules is accompanied by gradual increases in F and F/P_2O_5 on the continental shelves off Chile and Namibia (Baturin and Shishkina, 1973); 2) pore waters display fluoride gradients that require diffusion from sea water into the sediment column off Peru (Froelich and others, 1983); 3) F/Cl decreases below normal values in seawater across the sediment-water interface in Bermuda, suggesting F deposition into bottom sediments (Gaudette and Lyons, 1980); and 4) modern phosphorites show low CO_2 and F/P_2O_5 values compared with ancient, indicating enrichment in CO_2 and F during phosphorite diagenesis (Nathan, 1984). These studies suggest that bottom sediment phosphate grains are initially F and CO_2 deficient, but absorb these components from seawater during diagenesis, which "fixes" the phosphate minerals in geochemically stable forms. If these assumptions are valid, then individual phosphate grains from ancient deposits should exhibit F values that systematically vary from low (cores) to high (margins).

MINERALOGY AND GENESIS OF PHOSPHORITES

The principal mineral in phosphorites is apatite, which McClellan and Lehr (1969) have depicted as an isomorphous series with the species having generalized empirical formulas:

fluorapatite	-	dahllite	-	francolite
$Ca\,PO_4\,F$		$Ca\,PO_4\,(OH, F)$		$X\,(PO_4, CO_3.F)\;F$

McClellan (1980) has concluded that dahllite and francolite are metastable with respect to fluorapatite; the geologic consequence of this metastability is that these minerals systematically alter to fluorapatite as a result of weathering.

The formation of an economic-grade phosphorite (>15%P) in the marine environment represents a 2 million-fold enrichment in P from an average sea water content of ~0.07 ppm (Bentor, 1980), and involves biological accumulation of P, formation of stable phosphate minerals, and mechanical concentration of the stable mineral grains.

The accumulation of large quantities of P in biogenic debris is not difficult as many marine organisms incorporate more than 1% P in their soft tissues and hard parts, although abnormally high biological productivity and moderate water depths are required for high fluxes of biogenic detritus to sediment. Such requirements are best fulfilled in areas of coastal marine upwelling, which constitute less than 1% of the oceanic area, yet probably contain 50% of the total marine biomass (Ryther, 1963).

The mechanisms of phosphate mineral formation are hotly debated with arguments focused on whether apatite is formed through direct precipitation (Kramer, 1964; Roberson, 1966; Burnett, 1977) or by replacement (Ames, 1959; Cook, 1976). However, more recent studies (Bentor, 1980; Slansky, 1986) indicate that both direct precipitation and replacement mechanisms are likely to be operative.

Another major question with regard to apatite formation in phosphorite deposits is whether the mineral has formed above (Riggs, 1980) or below (Burnett, 1977) the sediment-water interface. Thus far, available data do not allow for a choice between these options although Baturin and Shishkina (1973) have shown that fluorine content apparently increases with the degree of apatite crystallization. Finally, several researchers (Cook, 1976; Burnett, 1977; Kolodny, 1980; Baturin, 1982) believe that mechanical reworking of apatite-rich sediment is necessary for concentrating the phosphate grains into economic accumulations.

MARINE PHOSPHORITE OF THE AURORA PHOSPHATE DISTRICT

Phosphorite in the Aurora Phosphate District (Figure 1) is of economic grade with mined ore (12% P_2O_5) beneficiated to a calcined product containing 33% P_20_5 (Notholt, 1980). The phosphorites contain three primary sediment components (phosphate, carbonate and terrigenous siliciclastics) which exhibit cyclic depositional patterns repeated at varying scales (Riggs, 1984a).

STRATIGRAPHY

The phosphorite horizons occur in the Miocene Pungo River and Pliocene Yorktown Formations. These formations correspond to 2nd-order global sea level cycles (Figure 2) bounded by major unconformities. A typical geologic cross section for the District is shown in Figure 3.

The Pungo River Formation is persistent with only minor lateral lithologic variation, although vertically smaller-scale, cyclic units (A, B, C, and D) separated by unconformities have been identified (Riggs, 1984b). In each of these units three lithofacies cycles are repeated: lower terrigenous-dominant phosphorite quartz sands grade upward into clay-rich phosphoritic sands, that are, in turn, capped by carbonate deposits. This lithic sequence reflects smaller-scale cycles within the major cycle. The Yorktown Formation contains "lower" and "upper" units, separated by a minor unconformity, with only the lower unit containing phosphorite.

BULK COMPOSITION

As with all marine phosphorites, those of the Aurora Phosphate District form as material aggregates containing particles of varying sizes. Macrograins consist of pellets (pseudo oolites), intraclasts and skeletal grains. However, when examined petrographically these macrograins are found to consist of microcrystalline material with apatite as the major component. The fine-grained "groundmass" materials of phosphorites are made up of crypto-and micrograined siliceous, calcareous and organic aggregates (Riggs, 1979).

SAMPLING AND SAMPLE DESCRIPTION

The macrograins (pellets, intraclasts and skeletal grains) analyzed in this study were extracted from drill hole 391 (see Figures 1 and 3), which intersected phosphate-bearing sediments at elevations between 80 and 160 feet below mean sea level (Table 1).

The sediments are unconsolidated with phosphate grains occurring as loose particles or in friable lumps of admixed phosphate and exogangue (predominantly quartz, dolomite, calcite, clay minerals). Pellets and intraclasts are generally much coarser than skeletal grains, attaining pebble size (>2 mm), although most are between fine sand and sand sizes (0.062 - 0.2 mm). Pellets are ovoid in shape and have resinous or glazed surfaces, while intraclasts are angular and have a dull, corroded appearance. The skeletal grains are a mixture of fossil vertebrate remains, as well as invertebrate shells and fish scales.

All three grain types were present in every sample. In a few cases, grinding by mortar and pestle was necessary to break up the lumps and liberate individual macrograins, while clay-sized particles were removed by wet sieving through a 220-mesh screen. The macrograins were then sorted from the residual sand fraction by hand-picking under a binocular microscope.

Table 1. Elevations and stratigraphic units sampled from phosphorites in drill hole 391 (this study), Aurora District, North Carolina

Elevation below MSL (ft)	Formation	Unit
-80.5	Yorktown	Lower
-83	Yorktown	Lower
-87.8	Yorktown	Lower
-90	Pungo River	D
-93.5	"	C
-99	"	C
-100.5	"	C
-104	"	C
-110	"	C
-114.5	"	B
-121	"	B
-127	"	B
-131.5	"	B
-137	"	B
-143.5	"	A
-145.5	"	A
-155.5	"	A

ANALYTICAL RESULTS

Individual macrograins were analyzed for F, P, Ca, Na, Si and Fe using a JEOL (Model JXA-50A) Electron Microprobe at Northern Illinois University. Fluorapatite from Durango, New Mexico (USNM 104021) was calibrated as the reference material (Table 2).

In order to determine the elemental distributions within macrograins, they were systematically analyzed from core to margin for F, P and other elements, and it was assumed all F and P analyzed occurred in the phosphate minerals. The number of locations analyzed within each grain depended on grain size, and spaces between measurements were uniform.

The weight percent ratios of F to P_20_5 were then calculated from the analytical data for each grain. As the F:P_20_5 can

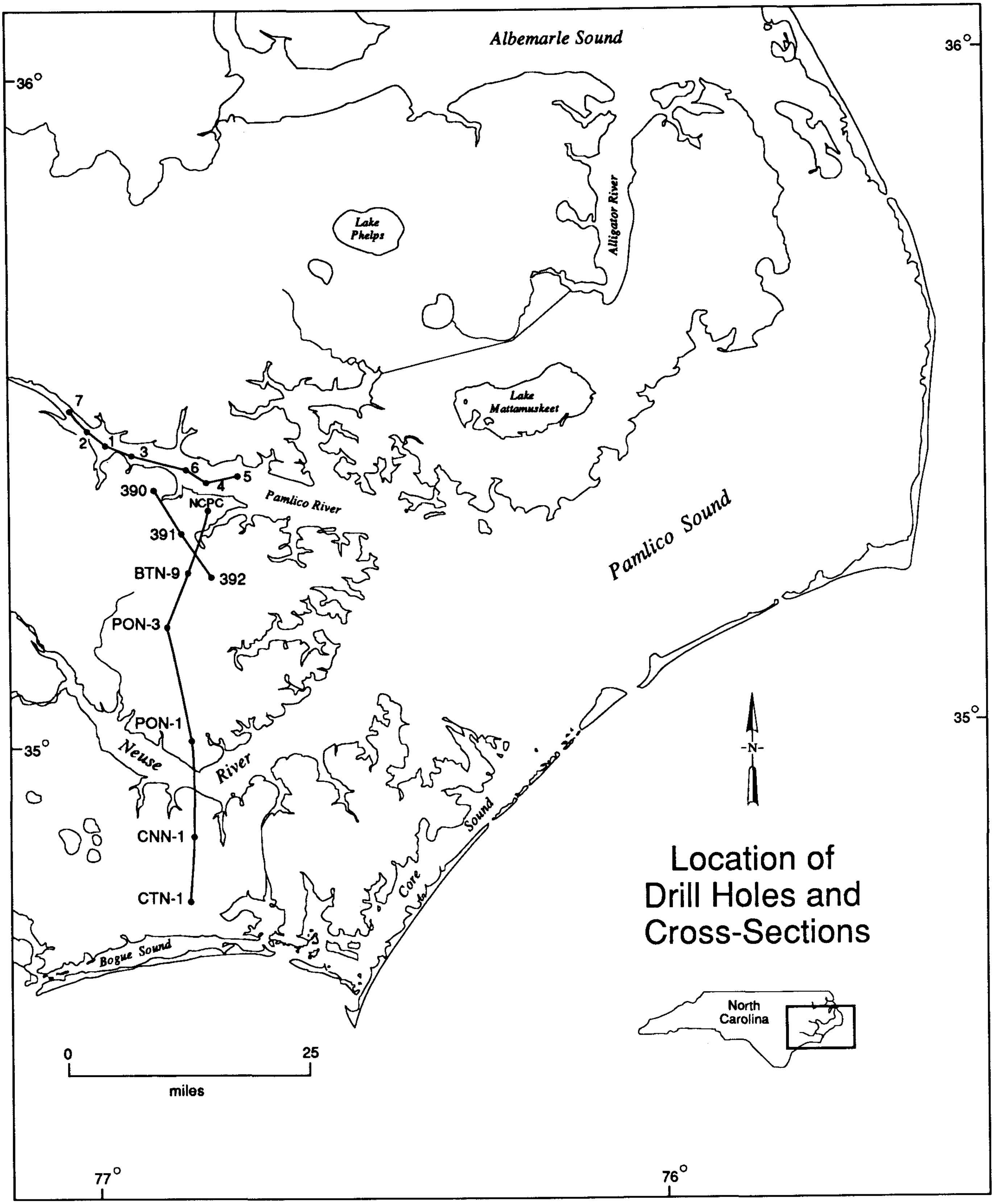

Figure 1. Location of the Aurora Phosphate District and drill holes 390, 391, and 392 (after Snyder and others, 1986).

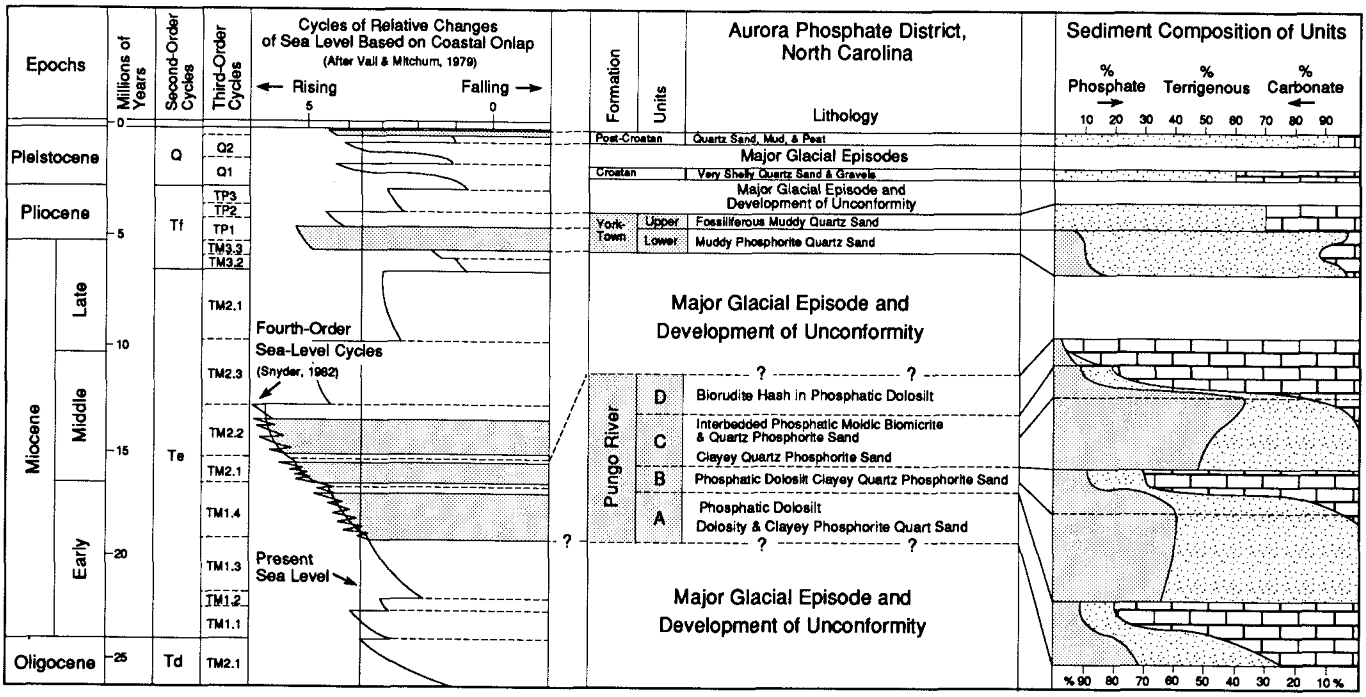

Figure 2. Stratigraphic section of the Aurora Phosphate District showing the Neogene phosphate units, the cyclical pattern of terrigenous, phosphate and carbonate sedimentation within each lithologic unit, and the relationship of sedimentary units to second- and third- order cycles of global sea-level fluctuations (after Riggs, 1984a).

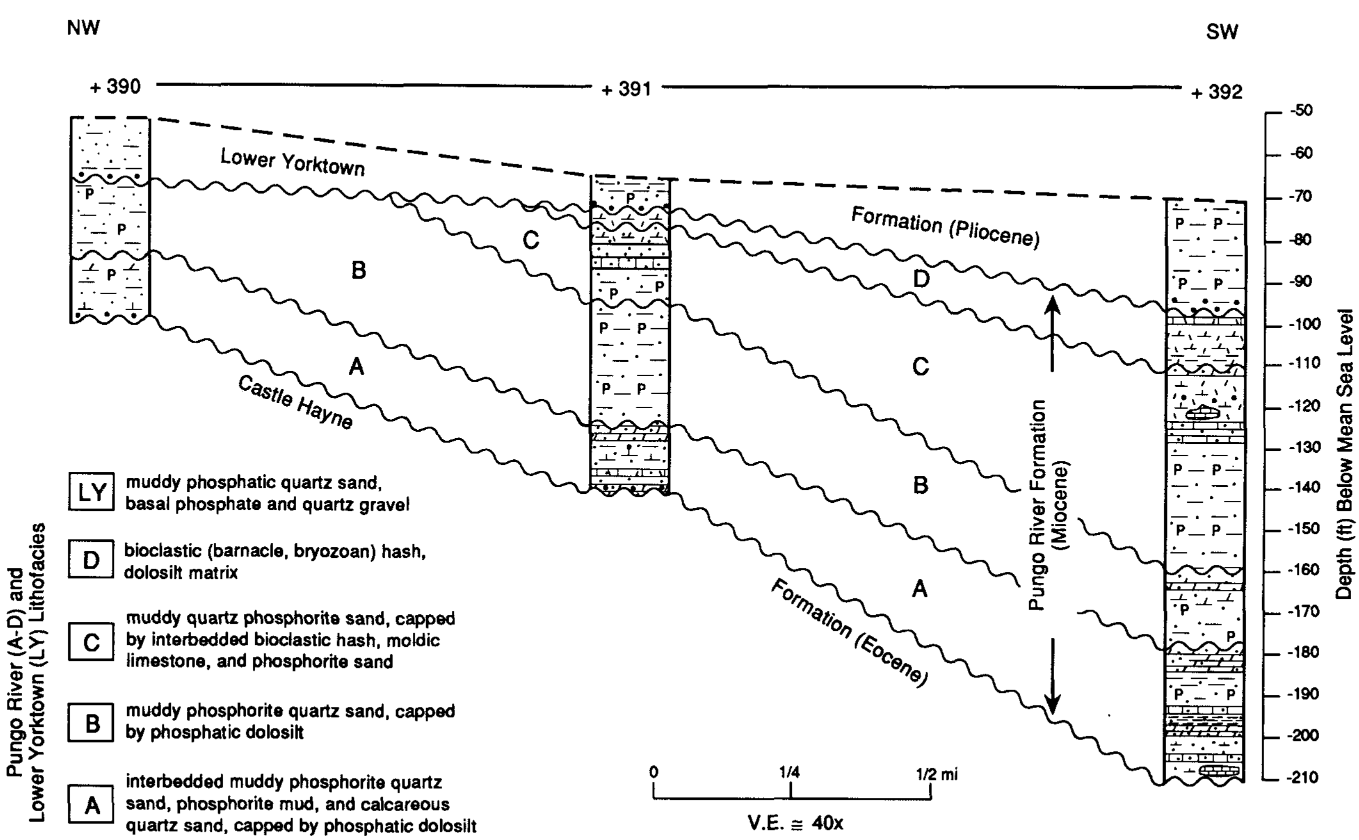

Figure 3. Lithologic correlation of drill holes 390, 391, and 392, Aurora Phosphate District. Core locations are shown in Figure 1 (after Snyder and others, 1986)

Table 2. Calibration results on the JEOL (Model JXA-50A) Electron Microprobe, Northern Illinois University, for mineral standard USNM 104021 (Fluorapatite), Durango, NM using an average of ten determinations

	This study wt %	Reported values wt %
F	3.33	3.53
P_2O_5	41.35	40.78
CaO	54.29	54.02
Na_2O	tr	0.23
SiO_2	0.41	0.34
Fe_2O_3	tr	0.06
Total	99.38	98.96

tr = trace

vary with either F content or P content or both, it was necessary to determine which element most directly affected this ratio. The results shown in Figures 4 and 5 indicate that the F/P_2O_5 ratio is highly dependent on F values within pelletal macrograins. In addition there is a consistent F distribution in the pelletal macrograins of carbonate facies, with values increasing from cores to margins. This pattern is not observed in either the terrigenous facies pelletal grains or the other macrograin types (Tables 3 and 4), which supports the concept that they evolved under different physical conditions (Riggs, 1979; Ellington, 1984).

Carbonate facies macrograins display higher F/P_2O_5 values than terrigenous facies and all analyses show considerable ranges of values, which we believe supports the isomorphous substitution model of McClellan (1980) and McClellan and Lehr (1969), in which F content correlates directly with the amount of CO_3 in the apatite structure. If this correlation is correct we believe our data support the investigations of Borneman- Starynkevich and Belov (1940), Smith and Lehr (1966), Price and Calvert (1978), Bentor (1980), Nathan (1984), and McArthur(1985)which show that group (CO_3F^{3-}) substitution is probably involved in francolite formation (carbonate facies). We believe it is likely that such substitu tions would take place during diagenesis.

As terrigenous sedimentation here was associated with regressive (offlap) phases of the sea level cycle that produced the Pungo River and Yorktown Formations (Riggs, 1984b), it is likely that subaerial weathering resulted in partial conversion of francolite to fluorapatite, thus accounting for the observed decreases in F and F/P_2O_5 values in terrigenous facies macrograins. Our analyses yielded no observable relationship between F content (F/P_2O_5) and age (depth).

Table 3. Microprobe values and ranges of values (wt percent) determined for F, P_2O_5 and F/P_2O_5 from intraclast macrograins, by lithofacies type for phosphorites, Aurora District, North Carolina

Carbonate Facies	Core	Interior	Margin
Lower Yorktown			
F	4.2	2.8 - 3.8	2.11 - 3.2
P_2O_5	27.0	21.8 - 30.1	24.8 - 30.8
F/P_2O_5	0.16	0.08 - 0.15	0.07 - 0.12
Pungo "C"			
F	2.75	3.0 - 3.8	2.8 - 3.0
P_2O_5	23.5	20.2 - 25.5	18.7 - 21.0
F/P_2O_5	0.11	0.13 - 0.15	0.12 - 0.15
Pungo "A"			
F	3.9	3.0 - 5.1	3.4 - 3.6
P_2O_5	27.3	26.2 - 31.7	31.1 - 31.5
F/P_2O_5	0.14	0.10 - 0.16	0.11 - 0.12
Terrigenous Facies			
Pungo "C"			
F	3.0	3.1 - 3.2	1.2 - 6.1
P_2O_5	24.0	26.9 - 27.9	26.2
F/P_2O	0.13	0.11	0.10 - 0.18

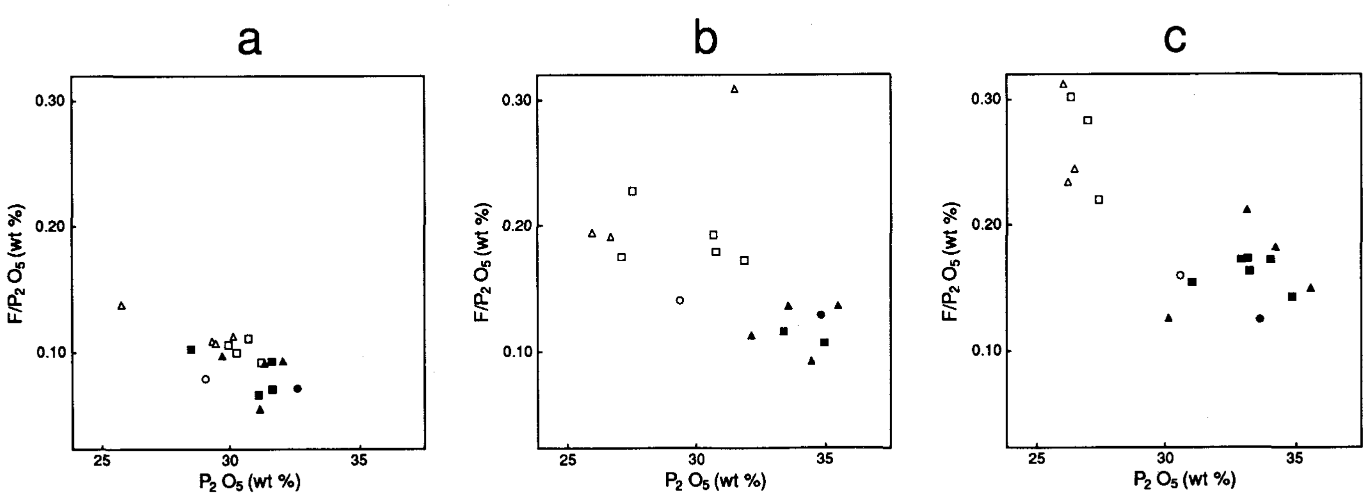

Figure 4. Plot of F/P_2O_5 (wt %) vs. P_2O_5 (wt %). Data are for pelletal macrograins from (a) Lower Yorktown Unit, (b) Unit "C" of Pungo River Formation, and (c) Unit "A" of Pungo River Formation, Aurora District. Open symbols are carbonate facies; solid symbols are terrigenous facies. Circles = core; box = interior, triangle = margin.

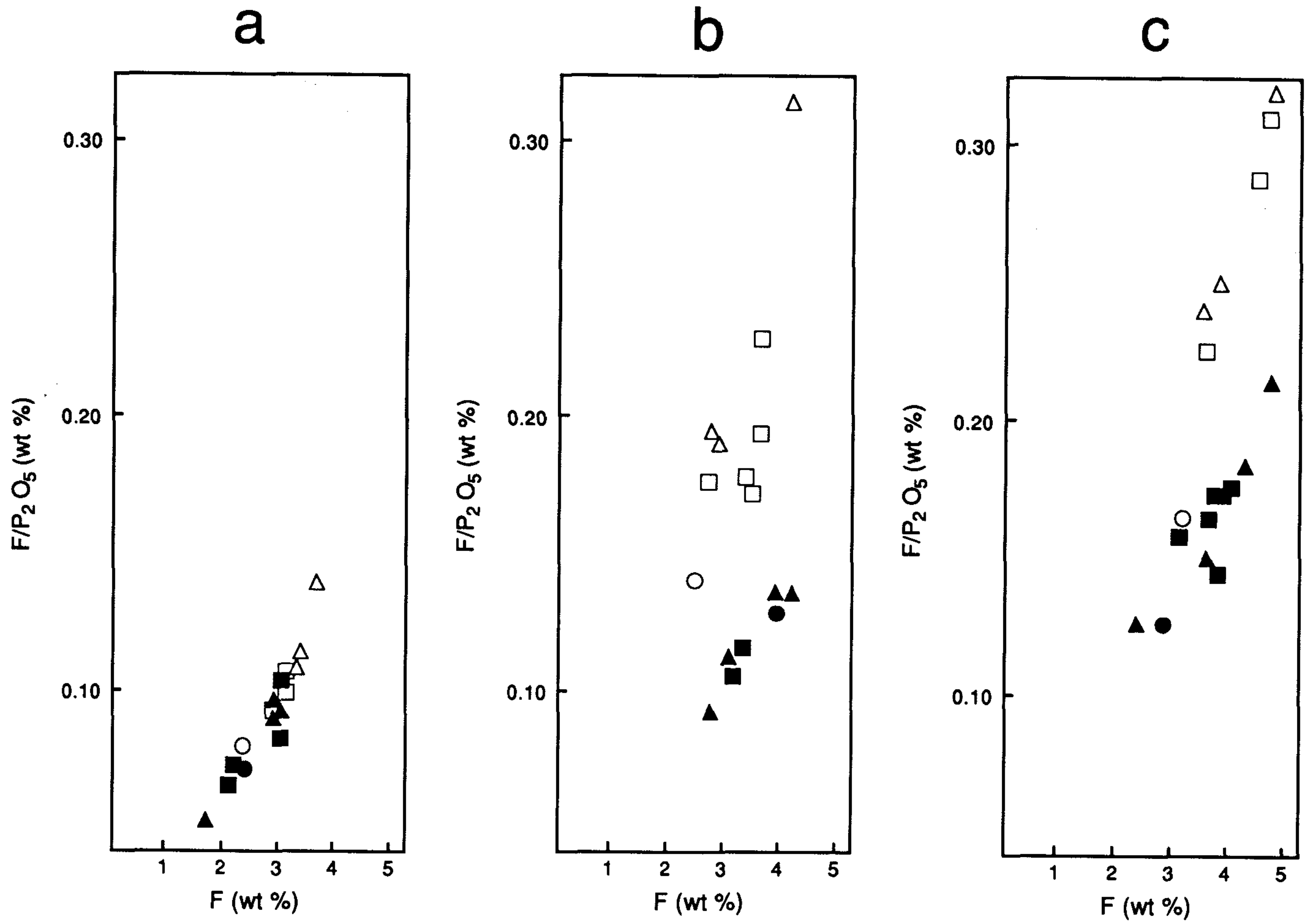

Figure 5. Plot of F/P_2O_5 (wt %) vs. F (wt %). Data are for pelletal macrograins from (a) Lower Yorktown Unit, (b) Unit "C" of Pungo River Formation, and (c) Unit "A" of Pungo River Formation. Open symbols are carbonate facies; solid symbols are terrigenous facies. Circles = core; box = interior, triangle = margin.

CONCLUSIONS

We have analyzed macrograin samples from drill cores penetrating phosphorite horizons in the Aurora District by microprobe analysis and determined that F content provides the major control in determining the F/P_2O_5. Our analyses show that pelletal macrograins from carbonate facies phosphorites exhibit increased fluorine values from cores to margins. Such a distribution supports the hypothesis that fluorine was gradually incorporated into the "starting" apatite grains producing carbonate fluorapatites, most likely during diagenesis. Intraclast and skeletal macrograins and terrigenous facies pellets show irregular fluorine distributions, which we believe to result from post formation weathering and transport.

Pellets, intraclasts and skeletal grains formed in different environments and by different mechanisms. That they exist together in phosphate horizons implies that mechanical reworking and winnowing is important in concentrating the grains into phosphorite deposits of commercial value. The process of ore formation by mechanical concentration has two requirements. First, the P-enriched mineral must be relatively heavy so that as the sediments are winnowed, the mineral remains behind as lag deposits, and apatites have specific gravities that exceed 3. Secondly, the mineral must be sufficiently resistate (both chemically and mechanically) to permit incorporation into the host sediment after mechanical reworking. We believe the gradual accumulation of fluorine into the apatite structure, which we have documented has imparted these properties to the pelletal macrograins of the Aurora District.

Table 4. Microprobe values and ranges of values (wt percent) determined for F, P_2O_5 and F/P_2O_5 from skeletal macrograins by lithofacies type for phosphorites, Aurora District, North Carolina

	Core	Interior	Margin
Carbonate Facies			
Lower Yorktown			
F	2.8	3.1 - 3.5	3.1 - 3.8
P_2O_5	28.2	30.8 - 34.7	29.7 - 35.9
F/P_2O_5	0.10	0.10 - 0.11	0.09 - 0.12
Pungo "C"			
F	3.2	2.3 - 2.6	1.8 - 3.0
P_2O_5	27.2	23.8 - 29.5	22.2 - 30.0
F/P_2O_5	0.12	0.09 - 0.10	0.10
Pungo "A:			
F	3.5	3.8 - 4.2	3.2 - 4.7
P_2O_5	19.2	25.2 - 25.4	17.6 - 21.3
F/P_2O_5	0.18	0.16 - 0.17	0.19 - 0.25
Terrigenous Facies			
Pungo "C"			
F	3.0	2.5 - 2.7	2.5 - 3.8
P_2O_5	30.0	31.2 - 33.2	30.5 - 32.9
F/P_2O_5	0.10	0.08	0.07 - 0.12

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PEGMATITE INVESTIGATIONS IN GEORGIA

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ABSTRACT

In the southeastern United States, the Appalachian pegmatite province consists of at least two pegmatite belts: the Blue Ridge belt and the Piedmont belt. Within these belts in Georgia, most pegmatites are clustered in twelve distinct districts: Cherokee-Pickens, Lumpkin-Union-Towns, Thomaston-Barnesville, Jasper, Putnam, Hartwell, Troup, Rabun, Carroll-Paulding, Oconee, Crawford-Jones-Baldwin, and Habersham. Regional-scale, Appalachian-age thrust faults commonly mark the boundaries of these pegmatite districts. Preliminary studies indicate that pegmatites in at least three of the districts in the Piedmont Belt in Georgia have distinctive internal zoning, size and bulk mineralogy. The host rocks are generally staurolite to sillimanite grade quartz-mica gneiss and schist; however, the more competent rock units, generally igneous intrusions such as the Gladesville Norite (Jasper district) and the Jeff Davis "granite" (Thomaston-Barnesville district), are particularly well suited to hosting the larger and generally more economic pegmatite bodies. Although post-metamorphic, granitoid plutons are common in Georgia, most of the pegmatite districts do not appear to be spatially or genetically related to them. The only clear association of pegmatites and potential source intrusion occurs in the Shady Dale intrusive complex (Jasper district).

Past mining of pegmatites, encouraged by high prices during World War I and World War II, yielded beryl, feldspar and sheet mica. During World War II, mica production (over 146,000 lbs.) in the Georgia Piedmont accounted for 41% of the mica produced in the southeastern Piedmont (Jahns and others, 1952). Post World War II mining of the pegmatites yielded moderate amounts of beryl, minor quartz, lower quality bulk mica, and significant quantities of feldspar.

Current and recent investigations by the Georgia Geologic Survey are focused on a re-examination of the pegmatites - their distribution, geochemistry and petrogenesis, with a particular emphasis on evaluating their rare-element potential. Although most of the pegmatites appear to belong to the mica-bearing type of Cerny (1982a), Gunow and Bonn (1989) demonstrated that rare-elements (Be, Nb, Li, Ba, F and Rb/K) are enriched in the more strongly fractionated pegmatites of the Cherokee-Pickens district. Concentrations of beryl and Ta-bearing pegmatites in the Troup, Oconee, Cherokee-Pickens, and Putnam districts indicate a strong potential for rare-element pegmatites overlooked during earlier prospecting for mica- and feldspar-bearing deposits.

INTRODUCTION

The Appalachian pegmatite province extends from Alabama into Maine. Pegmatites in the southernmost portion of the province are concentrated in two distinct belts: the Blue Ridge and the Piedmont (Jahns and others, 1952). Earlier studies which focused on the sheet mica-bearing pegmatites (Furcron and Teague, 1943; Heinrich and others, 1953; Gunow and Bonn, 1989) recognized six pegmatite districts: 1) Rabun, 2) Lumpkin-Union-Towns, 3) Cherokee-Pickens, 4) Hartwell, 5) Thomaston-Barnesville, and 6) Troup. The current investigation suggests an additional six districts are present (Figure 1): 7) Habersham, 8) Carroll-Paulding, 9) Oconee, 10) Jasper, 11) Putnam, and 12) Crawford-Jones-Baldwin.

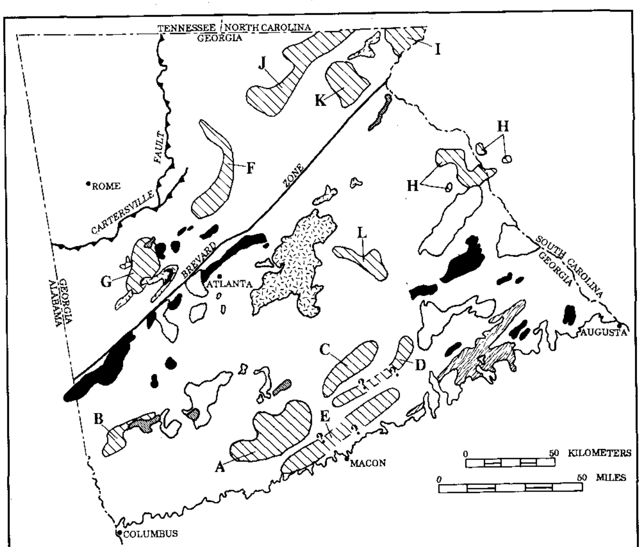

Figure 1. Relation of Pegmatite Districts to Granitic Intrusions in Georgia. (Location of intrusions from Higgins and others, 1988)

PEGMATITE DISTRICT

- A Thomaston - Barnesville
- B Troup
- C Jasper
- D Putnam
- E Crawford - Jones - Baldwin
- F Cherokee - Pickens
- G Carroll - Paulding
- H Hartwell
- I Rabun
- J Lumpkin - Union - Towns
- K Habersham
- L Oconee

GRANITES

- Carboniferous granites
- Silurian - Devonian granites
- Pre-middle Ordovician granites (mostly Cambrian)
- Granite-granite gneiss complexes of more than one age
- Granites of unknown age

Figure 1. Relation of pegmatite districts to granitic intrusions in Georgia (location of intrusions from Higgins and others, 1988).

MINING ACTIVITIES

During World Wars I and II, supplies of sheet mica were restricted, causing an increase in demand. Higher, subsidized prices encouraged prospecting and mining of mica-bearing pegmatites in Georgia. Beryl was also mined locally as a strategic mineral. Extensive mining of potassic and sodic feldspar-bearing pegmatites began during the 1950s. Although current production of feldspar, sheet and flake mica, and beryl from pegmatites is greatly reduced in Georgia, the potential is encouraging for further development.

Initial mica production in Georgia was centered in the northern part of the Blue Ridge pegmatite belt. Prior to 1908, most of the mica production in Georgia was from the Lumpkin-Union-Towns district. From 1909 to 1918, the Cherokee-Pickens district was the leading producer. Dwindling reserves in the Blue Ridge, the discovery of rich, mica-bearing pegmatites in the Piedmont, and the ease of saprolite vs hard-rock mining all probably contributed to the shift of production to the Thomaston-Barnesville and Hartwell districts in the Piedmont belt. During the period 1917-24, output from the Thomaston-Barnesville district is estimated at several hundred thousand pounds of trimmed mica (Heinrich and others, 1953). During World War II, the Thomaston-Barnesville district was the leading producer of sheet and punch mica in the southeastern Piedmont of the United States with 114,165 pounds or 32 percent of the total production (Jahns and others, 1952). Sixty-two percent of this production came from 4 mines: Adams, Battles, Early Vaughn and Mitchell Creek (Heinrich and others, 1953). Although published, comprehensive data is incomplete following World War II, production of sheet mica apparently continued in a few of the larger mines at a decreased level into the early 1960s when price subsidies were discontinued. Yearly production of sheet mica in Georgia ranged from 9,000 to 17,000 lbs./year during this period. Scrap and sheet mica production continues at the present time in a few mines in the Hartwell and Cherokee-Pickens districts (Gunow and Bonn, 1989).

Feldspar production from pegmatites is historically centered in the Jasper district, although several of the large, zoned pegmatites in the Thomaston-Barnesville district apparently produced potassic feldspar as a by-product of mica production. The Jasper district pegmatites contain mainly high-potassium (6-13%) feldspar (Whitlatch, 1962), although a soda-rich feldspar was produced from a large pegmatite near Enon Church toward the southern end of the district.

During the period 1952-1957, 178,300 pounds of beryl were produced from 5 pegmatite mines. Most of the production (172,400 lbs.) was from the Foley or Hogg mine in Troup County. The remainder was produced from the Bennett and Cochran mines (4,000 lbs.). (Reno, 1956)) and the Denson Mines (1,500 lbs.) in the Cherokee-Pickens district, and from the High Shoals area (400 lbs.) in the Oconee district (Furcron, 1959). Renewed production is currently underway at the Cochran mine (J. Connor, 1990, personal communication) with 200,000-240,000 lbs. of beryl produced during 1985 (Gunow and Bonn, 1989).

The large quartz-cored pegmatites in Putnam County were briefly mined by the Quartz International Corporation (Koch and others, 1984 and 1987). The amount of production is unknown, but based on the size of the workings, amounted to less than 100 tons.

PREVIOUS STUDIES

Prior to World War I, there are no comprehensive studies of Georgia pegmatites. The first investigation (Galpin, 1915), located and described numerous aplite dikes in addition to the feldspar and mica pegmatites. Because of the scarcity of prospecting or development up to that time, many pegmatites were not recognized. Furcron and Teague (1943) described a significantly larger number of mica-bearing pegmatites that had been discovered and developed during the war and during the initial stages of World War II. Pegmatite investigations (Beck, 1948; Jahns and others, 1952; Griffitts and Olson, 1953; Heinrich and others, 1953) attained a high level of intensity with the extensive prospecting for and development of mica-bearing pegmatites throughout the southeastern Piedmont. These investigations provide important information on the mineralogy, internal zoning and structure of the pegmatites in the southeastern Piedmont. Because of the extensive weathering and the present scarcity of fresh exposures, this information on the pegmatites is impossible to verify at this time.

Despite the continuation of mica mining into the early 1960s and the development of feldspar-rich pegmatites, pegmatites in Georgia generally have been ignored in the geologic literature. Occasional mineral resource studies on counties or regions contain locations and brief descriptions of the pegmatite mineralogy (Hurst and Crawford, 1964; Hurst and Otwell, 1964). Pegmatites often are noted as mineral collecting localities (Cook, 1978), but little new information has been generated.

Recently, Gunow and Bonn (1989) studied the geochemistry of pegmatite micas in the Cherokee-Pickens district as part of the Accelerated Minerals Program of the Georgia Geologic Survey. Current investigations involve the sampling of mica and feldspar from pegmatites throughout Georgia.

CLASSIFICATION OF GRANITIC PEGMATITES

Granitic pegmatites are coarse-grained, dike-like intrusions generally composed of various proportions of quartz, mica (generally muscovite), and feldspar (generally potassic or sodic). One or more accessory minerals also may be present. Granitic pegmatites are classified on the basis of geological-petrogenetic criteria developed by Ginsburg and others (1979) and recently introduced into North America by Cerny (1982a). The four basic types of pegmatites are: 1) miarolitic pegmatites, 2) rare-element pegmatites, 3) mica-bearing pegmatites, and 4) maximal depth pegmatites (Cerny, 1982a). Brief descriptions of each type given below are based on Cerny (1982a).

Miarolitic pegmatites occur as pods in the upper parts of epizonal granite intrusions that are emplaced into low-grade metamorphic country rocks. These pegmatites are characterized by crystal-lined cavities containing quartz, fluorite, beryl, topaz, etc.

Rare-element pegmatites generally occur in cordierite - amphibolite facies metamorphic rocks peripheral to differentiated allochtonous granites. These pegmatites are formed at

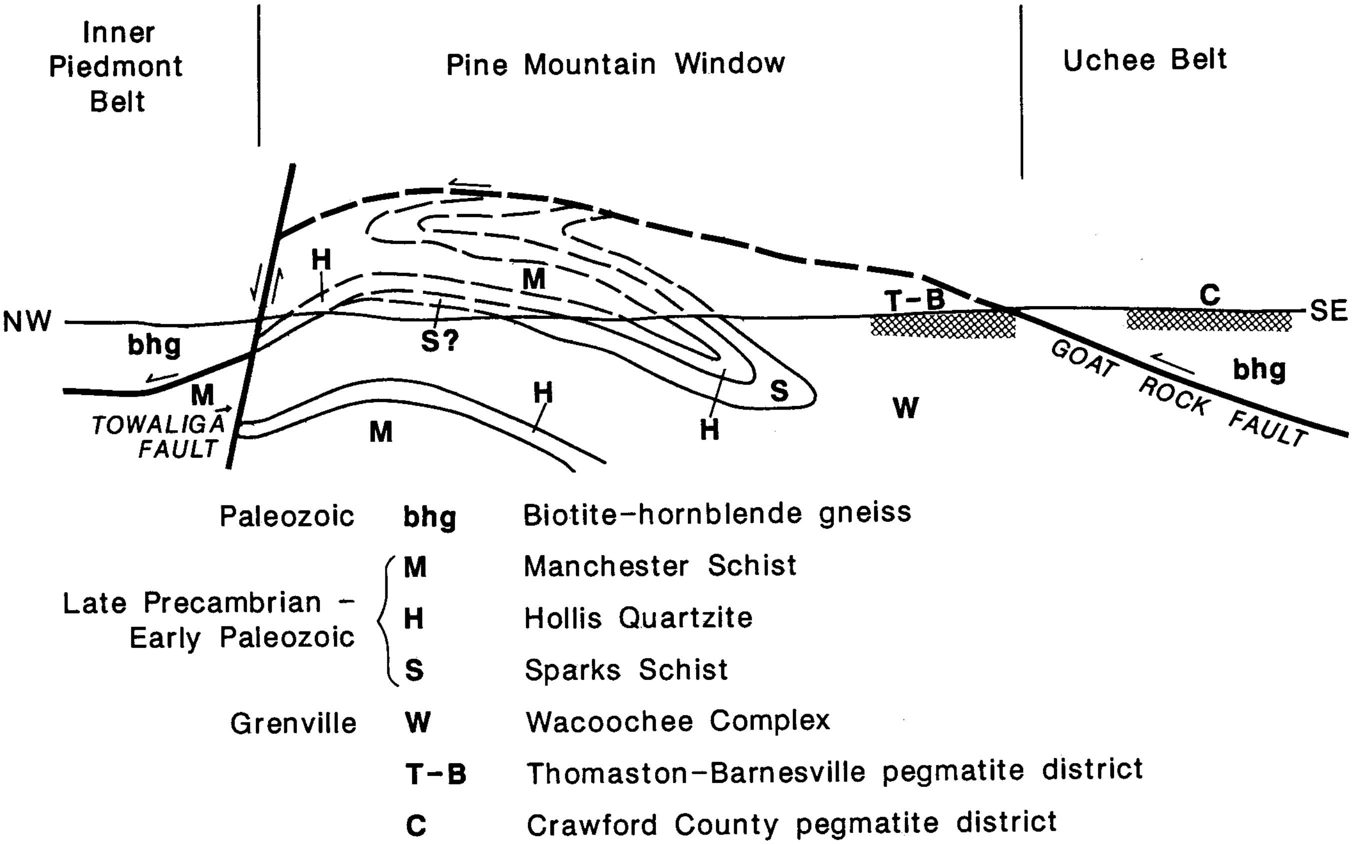

Figure 2. Location of pegmatite districts in relation to the Pine Mountain window and adjacent terranes, Georgia (modified from Schamel and others, 1980).

pressures equivalent to intermediate depths (3.5-7 km). These pegmatites are enriched in one or more of the following elements: Li, Cs, Rb, Be, Ta, Sn and Nb.

Mica-bearing pegmatites are formed at pressures equivalent to depths of 7 to 11 km in almandine-amphibolite facies metamorphic rocks. Although occasionally containing rare-elements, they are primarily important for their mica content. Commonly, no source intrusion is apparent for these pegmatites, which suggests that their genesis is by anatexis or by separation from an anatectic, more or less autochthonous granite.

Maximal depth pegmatites are formed at pressures equivalent to depths greater than 11 km. These pegmatites occur in upper amphibolite- to granulite-facies terrains and commonly grade into migmatites. These pegmatites may be barren, allanite + monazite-bearing or ceramic (feldspar-rich).

In the southern part of the Appalachian pegmatite province, the most abundant types of pegmatites are the mica-bearing and the maximal depth pegmatites. Both of these types have been mined principally for their mica or feldspar content, respectively. The rare-element pegmatites are most notably represented in the Kings Mountain district, North Carolina. Pegmatites in the Oconee, Putnam, Cherokee-Pickens and Troup districts in Georgia have some characteristics of rare-element pegmatites, but have not been extensively studied. Miarolitic pegmatite districts are currently unknown in Georgia but could occur associated with the numerous granitic intrusions in the low-grade metamorphic rocks of the Carolina Slate Belt.

CHARACTERISTICS OF PEGMATITE DISTRICTS IN GEORGIA

To date, the current investigations have focussed on five districts: Thomaston-Barnesville, Jasper, Putnam, Crawford-Jones-Baldwin Counties, and Cherokee-Pickens districts. Extensive geochemical sampling has been done in each of these districts, but only the data from the Cherokee-Pickens district is presently available. Brief descriptions of these five districts follow.

THOMASTON-BARNESVILLE DISTRICT

Most of the Thomaston-Barnesville district's pegmatites occur in the 1 b.y. old Grenville-age Wacoochee Complex granitic rocks (Schamel and others, 1980) along the southern half of the Pine Mountain window (Figure 2). Granitic rocks have been mapped as Woodland Gneiss (Hewett and Crickmay, 1937) or Jeff Davis Granite (Clarke, 1952). The original, (1 b.y. Grenville-age) static, granulite facies metamorphism was overprinted by probably mid-Paleozoic, greenschist-amphibolite or lower amphibolite (kyanite) facies metamorphism (Schamel and others, 1980). The Wacoochee Complex and the overlying metasedimentary rocks of the Late Precambrian Pine Mountain Series have been remobilized and folded into two large nappes overturned to the northwest.

The pegmatites and the immediately surrounding host rocks are commonly deeply weathered and are poorly exposed. The pegmatites are composed predominantly of muscovite + quartz + feldspar and are probably mainly of the mica-bearing type. Beryl, tourmaline, garnet or apatite are present locally (Heinrich and others, 1953). The pegmatites are unzoned, poorly zoned, or distinctly zoned with two to five zones.

Extensive studies by Heinrich and others (1953) demonstrated that pegmatites with two zones contain an inner core of medium-grained granitoid rock and an outer core of (a) finer-grained granitoid rock, (b) burr rock composed of intergrown quartz and mica, or (c) mica-rich pegmatite. Pegmatite bodies with more than two zones have monomineralic or bimineralic cores with a thin selvage or border zone of fine-grained quartz-feldspar rock.

In the Thomaston-Barnesville district, mica was mined from three types of deposits: 1) disseminated mica, 2) wall-zone mica, and 3) core-margin (intermediate zone) mica. Although core-margin deposits are the most abundant in this district, wall-zone deposits accounted for a large portion of this district's mica production (Heinrich and others, 1953). Large quantities of perthite in several of the district's mines apparently were recovered during post-World War II operations.

The Thomaston-Barnesville pegmatites are small to medium in size. They range from 2 inches to 25 feet in width. Most of the pegmatites are less than 200 feet long, although a few are 200 to 1,000 feet in length. The vertical extent of these pegmatites is largely unknown, because mining rarely extended below 100 feet or the depth of weathering (Heinrich and others, 1953).

Approximately half of the pegmatites in the district are concordant to the gneissic foliation. The prevailing strike of both pegmatites and gneissic foliation is northeast and the general dip is southeast. More than half the pegmatites range in strike from N.0°E to N.60°E., and two-thirds of them range in dip from modestly southeast to vertical. Very few dips are less than 30 degrees (Heinrich and others, 1953).

Early mining in this district was by selective underground methods. Later, generally post-World War II, mining was by open-pit methods. This later mining appears to be mainly on the larger pegmatite bodies and may have resulted from collapse or from attempts to mine the pillars. Most mining activity was confined to the upper, weathered portion of a deposit (the upper 40 to 60 feet) which was much less expensive than hard rock mining. Systematic mining in the district began about 1916 with the most extensive mining confined to the periods, 1917-24 and 1941-45 (Heinrich and others, 1953).

JASPER DISTRICT

In Jasper County, south and southeast of Monticello (Figure 3), numerous large pegmatites form one of the most important pegmatite districts in Georgia. Geologic data on the pegmatites in this district is minimal. This lack of data restricts proper assessment of the district's potential. A thesis by Matthews (1967) provides most of the information on these pegmatites, but the primary focus of the thesis was on the Gladesville Norite - the host rock for most of the pegmatites.

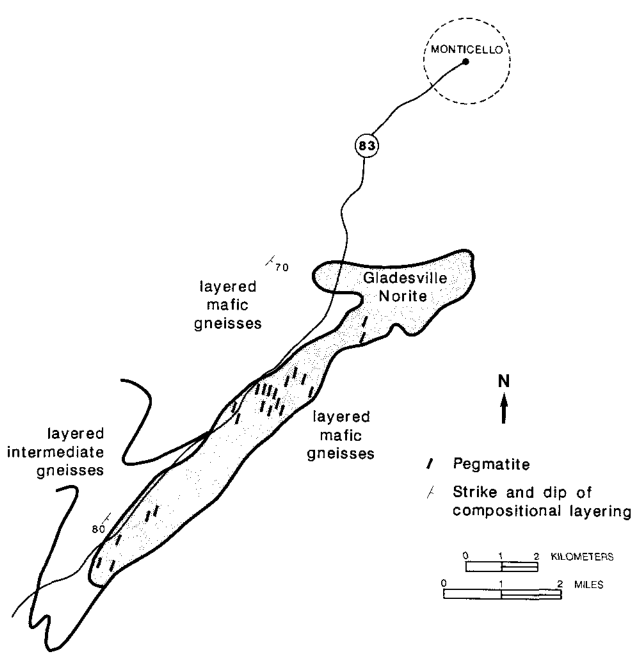

Figure 3. Generalized geology of the Jasper County pegmatite district (after Matthews, 1967 and Hooper, 1986).

The largest pegmatites, especially those that have been mined, occur within the Gladesville Norite, a Late Paleozoic?, composite, mafic pluton (Figure 3). Many other pegmatites occur in the adjacent hornfels (Matthews, 1967). The Gladesville Norite and the enclosing sequence of layered gneisses of mafic to felsic composition comprise what is called the Berner mafic complex (Hooper, 1986). Metamorphic grade is estimated to be at or below the greenschist facies-amphibolite facies boundary (Hooper, 1986). Pegmatites within the Gladesville Norite are oriented generally N-S and generally dip 60° W (Matthews, 1967). They commonly cluster in swarms or fields. These pegmatites are generally large, ranging from a few inches to more than 50 feet wide and up to 1000 feet in length (Cameron and Sparks, 1976).

The pegmatites in the Jasper district are distinct from those in adjacent districts in that they are composed mainly of graphic granite with only minor muscovite. Zoning is generally poorly developed. Where zoning is developed, it appears to consist of a fine-grained granitoid border zone that gradually becoming coarser over a distance of 1 foot. Where the grain size becomes greater than 1 inch, a zone of pink graphic granite of microcline and quartz occurs. Small masses (<2 feet) of quartz scattered on the mine dumps suggest a small core of massive quartz may be developed in some of these pegmatites. A pegmatite near Enon Church is conspicuously zoned with a sugary-textured, quartz-feldspar border zone, a blocky perthite intermediate zone and a quartz core (Matthews, 1967). Unusual vermiculite veins (altered from biotite) commonly cut across the wall zones of these pegmatites.

Prior to 1947, the pegmatites in the Jasper district were mined for road gravel. Recognition of their potential for ceramic feldspar led to the development of this district. Pegmatites within the district are no longer mined, because the open pit mining methods of dragline and bulldozer reached maximum safety and economic depths. Apparently none of the pegmatites have been bottomed by mining (Matthews, 1967).

A rare association in Georgia of pegmatites within a host sodic granitic intrusion is currently being mined near Shady Dale, Jasper Co. The pegmatites are K-feldspar rich with minor quartz and muscovite. In addition to numerous episodes of pegmatite intrusion and quartz veining, quartz and feldspar textures within one of the pegmatites are strikingly similar to the crenulate textures present in the porphyry-hosted molybdenum intrusive systems at Henderson and Mt. Emmons in Colorado and at Cave Peak in Texas (White and others, 1981). These pegmatites occur in a weakly foliated to non-foliated, muscovite + feldspar + quartz + garnet granite. Further study of this association at Shady Dale may provide evidence for a genetic link between the pegmatites and a source intrusion at Shady Dale and elsewhere in the Jasper district.

PUTNAM DISTRICT

The pegmatites of the Putnam district occur in rocks similar to the Berner mafic complex in the Jasper district. These pegmatites are characterized by their large quartz cores (>20 feet wide). The quartz cores, which are resistant to weathering and erosion, are exposed as conspicuous outcrops. The large, prehistoric "Rock Eagle" mound north of Eatonton is constructed of quartz blocks from one of these pegmatites. A narrow rim of feldspar and mica is occasionally exposed by mining or prospecting activity. Tantalum-bearing minerals are reported from at least one of these pegmatites (Cook, 1978). Predominantly feldspar-bearing pegmatites occur in the district, a few of which have been selectively mined. Scattered quartz-molybdenite veins are also reported nearby (Cook, 1978). Minimal exposures in this district limit determination of the geologic relationships between the different pegmatites.

CHEROKEE-PICKENS DISTRICT

In this district, the pegmatites occur in two fields (Holly Springs and Ball Ground) located in different thrust sheets which are separated by a barren thrust sheet. The host rocks are late Precambrian to early Paleozoic metasedimentary and metaigneous rocks metamorphosed to the kyanite grade (middle amphibolite- facies). The pegmatites are irregular, tabular or lenticular bodies which have widths ranging from less than 3 feet to 100 feet and lengths ranging from 15 feet to nearly 2000 feet (Gunow and Bonn, 1989).

While pegmatites in the two fields both appear to belong to the muscovite class of Cerny (1982a), they differ in mineralogy and geochemistry. In addition to muscovite, microcline, perthite, albite or oligoclase, and quartz, pegmatites in the Ball Ground field contain tourmaline +/- beryl. Gunow and Bonn further divide the Ball Ground pegmatites based on whether they are beryl-poor, beryl-bearing, or beryl-rich (the Cochran pegmatite). Several pegmatites are zoned with a quartz core, an intermediate feldspar-quartz-muscovite-garnet-tourmaline zone and a fine-grained border zone of feldspar-quartz-muscovite. Beryl, garnet or tourmaline may occur in the quartz core (Gunow and Bonn, 1989).

CRAWFORD-JONES-BALDWIN DISTRICT

Little data is available regarding the pegmatites or the geology of this district. No production is known, so information is restricted to the early work by Galpin (1915) and to the current investigation.

Pegmatites in the Crawford-Jones-Baldwin district occur within a poorly known metamorphic sequence known as the Uchee belt. The Uchee belt consists of layered, migmatitic biotite-hornblende gneiss and amphibolite of intermediate to mafic composition (Schamel and others, 1980). These are believed to be mainly metavolcanics metamorphosed to the sillimanite facies. In western Georgia, the Uchee belt consists of hornblende gneisses, amphibolites, gneissic metasediments, migmatites, and granitic to monzonitic gneisses (Hanley, 1986). It is separated from the Pine Mountain belt by the Goat Rock Fault (Figure 2), a major, regional thrust fault.

This district's pegmatites consist principally of potassic and sodic feldspar with minor quartz and uncommon muscovite. Most are relatively narrow (1 to 20 feet), although one may be as much as several hundred feet wide. In Crawford County, one swarm, which includes the previously mentioned thick pegmatite, trends northeast across the entire length of the county (Galpin, 1915) and may be of economic significance for its feldspar content.

BOUNDARIES OF DISTRICTS

Numerous NE-SW trending, major, regional thrust faults divide the Blue Ridge and Piedmont crystalline rocks into thrust slices. Pegmatite districts in Georgia are contained within individual thrust slices and are commonly bordered by a thrust fault (Figure 2). The location of a pegmatite district within a particular thrust slice is controlled by the favorable development of fractures within suitably competent and brittle host rocks (Jeff Davis Granite in the Thomaston-

Barnesville district and the Gladesville Norite in the Jasper district) and by the igneous/metamorphic conditions responsible for their genesis.

PETROGENESIS OF GRANITIC PEGMATITES

In general, granitic pegmatites are believed to crystallize from silicate melts. Silicate melts of granitic composition may be derived by anatexis of high-grade metamorphic rocks or by igneous fractionation from granitic intrusions. Although these concepts have been well documented, a source granite is commonly not readily apparent especially for the mica-bearing pegmatites and the maximal depth pegmatites. Frequently, a spatially close granite is mistaken for the source intrusion. Miarolitic pegmatites do occur within their source intrusion, and many rare-element pegmatites have been linked to "fertile" granites.

Maximal depth pegmatites and mica-bearing pegmatites are believed to be principally related to high-grade metamorphism. The maximal depth and mica-bearing pegmatites can be related to each other within a metamorphic series (Figure 4). Maximal depth pegmatites are formed during anatexis associated with upper amphibolite and granulite grade metamorphism. Mica-bearing pegmatites are distal to pegmatoid granites located in the cores and cupolas of migmatite domes in Barrovian-type metamorphic terrain. These granites are believed to be anatectic, near-autochthonous rocks. Igneous fractionation is thought to be minimal (Cerny, 1982b).

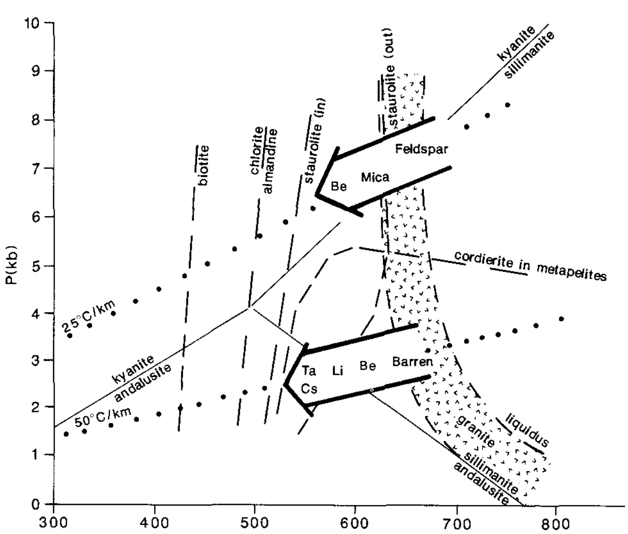

Figure 4. Relation of pegmatites to metamorphic facies series (modified from Cerny, 1982a; Gunow and Bonn, 1989). Explanation: Be-Mica-Feldspar is beryl-muscovite-"barren" maximal depth pegmatite series in Barrovian type sequence; Ta, Cs-Li-Be_Barren is Ta, Cs, petalite-spodumene-beryl-barren pegmatite series in Abukuma type sequence.

The rare-element pegmatites are commonly related to equigranular to porphyritic, generally small to moderate size, late- to post-tectonic granites of calc-alkaline intrusive sequences. Geochemical and mineralogical compositions indicate that the source granites are derived from considerably fractionated melts (Cerny, 1982b). These pegmatites are mainly developed in lower pressure, high temperature Abukuma-type metamorphic terrains (Figure 4).

Prior to the current availability of geochemical and isotopic data and the introduction of the Russian expertise on regional pegmatite zoning (Cerny, 1982a and b), the close spatial relationship of a granitic body to pegmatites was considered to be convincing evidence of a genetic relationship. Jahns and others (1952) noted that some mica-bearing pegmatites are spatially close to granitic intrusions in the Southeastern Piedmont of the United States, and acceptance of this inferred genetic relationship still exists within the geologic literature (Gunow and Bonn, 1989). However, within the Georgia Piedmont and Blue Ridge pegmatite belts, few of the pegmatite districts are spatially associated with any of the exposed granitic intrusions (Figure 1). The Shady Dale intrusive complex is an important exception and requires further study.

AGE OF PEGMATITES AND GRANITIC PLUTONISM

Isotopic age determinations suggest that the pegmatites and granitic plutons in the southeastern Piedmont and Blue Ridge formed during two periods of igneous/metamorphic activity: 350-340 m.y. and 325-265 m.y. (Fullagar and Butler, 1979). Numerous late Paleozoic granitic plutons (Figure 1), concentrated mainly southeast of the Kings Mountain belt, have yielded Rb-Sr age determinations of 325 to 265 m.y. (Fullagar and Butler, 1979). The Stone Mountain pluton yielded a Rb-Sr whole-rock plus mineral isochron age of 285 +/- 7 m.y. (Whitney and others, 1976).

Age determinations using the Rb-Sr method of pegmatites in the Blue Ridge belt of North Carolina indicate two distinct periods of formation: 350 m.y. and 500 m.y. (Deuser and Herzog, 1962). Gunow and Bonn (1989) report K-Ar ages of 356 +/- 20 m.y. and 338 +/- 5 m.y. for muscovites from the Cochran and Hillhouse pegmatites in the Cherokee-Pickens district. Gunow and Bonn suggest that these pegmatites were emplaced subsequent to or near the peak of regional metamorphism.

Age determinations of pegmatites from the Piedmont belt are consistently younger than those from the Blue Ridge belt. Rb/Sr age determinations yielded an apparent age of 296 +/- 16 m.y. for muscovite and 256 +/- 12 m.y. for biotite from the Mauldin mine in the Thomaston-Barnesville district. Rb-Sr age determinations of muscovites and biotites in Piedmont pegmatites average 285 m.y. (Deuser and Herzog, 1962). K-Ar age determinations for muscovite, albite and orthoclase from pegmatites in the Jasper district yielded apparent ages of 288 +/- 9 m.y., 360 +/- 11 m.y., and 233 +/- 7 m.y. respectively. The albite age is suspect as the K content is very low. Although a perthite, albite and muscovite-defined Rb-Sr isochron from a Jasper County district pegmatite indicates an age of 339 +/- 16 m.y. (Jones and others, 1974), the error limits bracket the two periods of pegmatite formation.

SOURCE OF THE PEGMATITES

Studies relating pegmatite geochemistry to potential source magmas in Georgia are few. An investigation of a Jasper district pegmatite produced an initial $^{87}Sr/^{86}Sr$ ratio of 0.7035 +/- 0.0005 for a perthite, albite and muscovite defined isochron (Jones and others, 1974). Jones attributed this low initial ratio to an upper mantle origin. Because this ratio is similar to the average of four samples from the Gladesville Norite, Jones and others (1974) suggest the pegmatitic fluids were derived at depth from a related magma. Initial $^{87}Sr/^{86}Sr$ ratios reported for granitic intrusions in east-central Georgia range from 0.7035 +/- 0.004 to 0.7052 +/- 0.0001 (Fullagar and Butler, 1979) and suggest that these pegmatites could have had isotopically similar sources as those granites. A granitic magma is petrochemically a more likely source of the pegmatites (Cerny, 1982b) in the Jasper pegmatite district than the magma which produced the Gladesville Norite.

PEGMATITE GEOCHEMISTRY

In the United States, numerous classic studies have focussed on the mineralogy, crystal chemistry and internal zoning of pegmatites (Cameron and others, 1949; Jahns and others, 1952; Jahns, 1955; Jahns, 1982). This information is extremely useful for evaluation of the pegmatites after they are located but is of limited value in regional studies.

The regional mineralogical and geochemical zoning, and the petrogenesis of the different types of pegmatites have been largely neglected in the United States. In the U.S.S.R. and more recently in Canada (Cerny, 1982a and b; Trueman and Cerny, 1982), pegmatite investigations have emphasized these subjects as a means of locating and identifying potential economic pegmatites.

Fractionation of a granitic magma generally produces a volatile-rich melt enriched in K, Na and Si. Commonly concentrated along with these are incompatible trace elements such as Be, Nb, Li, Cs, Ta, Rb, F, Sn and B. Their concentrations in the pegmatites are governed by the degree of fractionation, by their abundance in the source intrusion, and by the bulk composition of the source intrusion. Cerny (1982b) and Trueman and Cerny (1982) discuss in greater detail the various characteristics of "fertile" vs "barren" source intrusions.

Selective geochemical analysis of K-feldspar and/or muscovite has repeatedly demonstrated that their trace-elements are useful in determining fractionation trends within pegmatite districts and in assessing the economic potential of the pegmatites (Trueman and Cerny, 1982). This technique is particularly powerful in the Southern Appalachian pegmatite province because extensive weathering quickly reduces many surface and near surface rocks to saprolite. Muscovite is essentially unaffected by weathering and commonly is the only surface indicator of a mica-bearing pegmatite. Surprisingly, the feldspar in many feldspar-rich and mica-poor pegmatites is relatively fresh and can be sampled for trace-element content.

Current and recent investigations by the Georgia Geologic Survey are focussed on a re-examination of the pegmatites within Georgia with a particular emphasis on evaluating their rare-element potential. Gunow and Bonn (1989) demonstrated that rare elements (Be, Nb, Li, F and Rb/K) are enriched in muscovites from the more strongly fractionated pegmatites of the Cherokee-Pickens district. The beryl-rich pegmatite of the Cochran mine is geochemically distinct from beryl-bearing and beryl-poor pegmatites within the same pegmatite field (Figure 5).

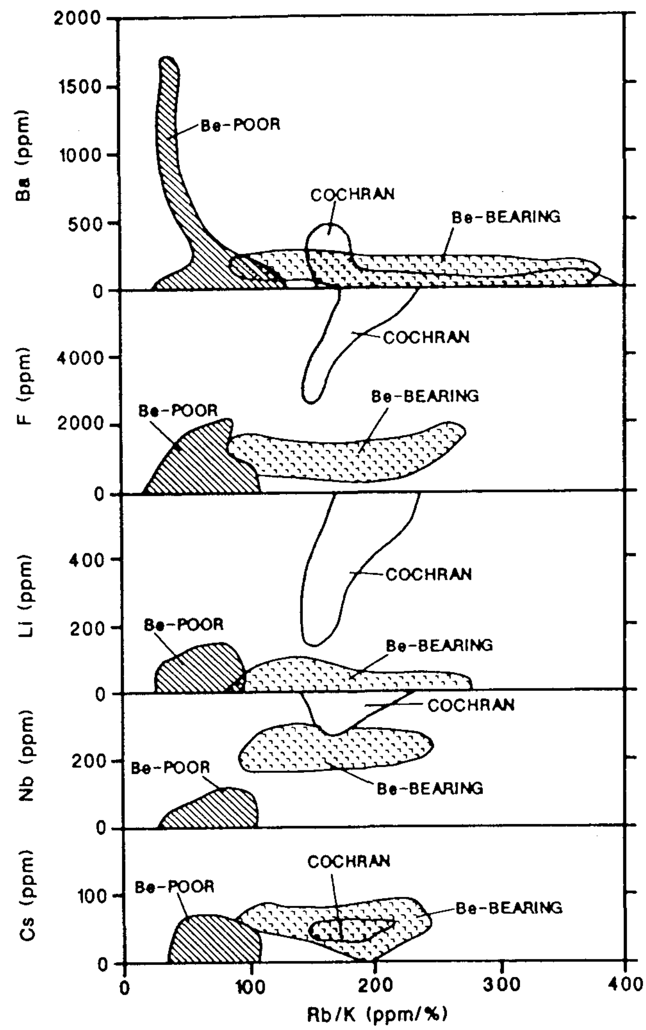

Figure 5. Trace elements in pegmatitic muscovite from Be-poor, Be-bearing and Be-rich pegmatites in the Ball Ground field of the Cherokee-Pickens district (modified from Gunow and Bonn, 1989).

Contouring of anomalous values on state-wide N.U.R.E. geochemistry maps, compiled by Koch (1988), indicate geochemically distinctive terrains. These terrains commonly appear to be related to Appalachian-age thrust slices. These will be correlated with the pegmatite geochemical data when it becomes available.

The presence of beryl and Ta-bearing pegmatites in the Troup, Putnam, Oconee and Cherokee-Pickens districts indicates a strong potential for rare-element pegmatites overlooked during earlier prospecting for mica- and feldspar-bearing deposits.

SUMMARY

Initially mined for sheet mica, pegmatites in Georgia have also been important sources of feldspar, "scrap" mica, and beryl. Preliminary results of current investigations by the Georgia Geologic Survey, suggest that the economic potential for pegmatites has not been realized in Georgia.

Most pegmatites occur within twelve distinct districts which form the Blue Ridge and Piedmont belts of the Appalachian pegmatite province. These districts, generally are not spatially related to exposed granitic intrusions, thereby suggesting that the origin of the pegmatites is more closely related to regional scale metamorphism and anatexis.

Isotopic age determinations of granites and pegmatites indicate that they did form during the same two periods. Genesis and emplacement of the granitic intrusions, regional scale metamorphism and anatexis may thus be broadly related. The Blue Ridge belt granites and pegmatites appear to be older than the Piedmont belt intrusions.

Fractionation of rare-elements during pegmatite genesis can be identified through geochemical analysis of muscovite and/or K-feldspar. Current investigations are focussed on this use of trace-element geochemistry to determine regional zoning relations and evaluate poorly exposed pegmatites.

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A RE-EVALUATION OF THE TAXONOMY OF NEWARK SUPERGROUP SAURISCHIAN DINOSAUR TRACKS, USING EXTENSIVE STATISTICAL DATA FROM A RECENTLY EXPOSED TRACKSITE NEAR CULPEPER, VIRGINIA

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ABSTRACT

An Upper Triassic bedding surface, recently exposed in the Culpeper Stone Company, Inc. quarry, has revealed about 2,000 reptile tracks. About 1,500 of these tracks, arrayed in 20 trackways, probably represent a single biological species of tridactyl bipedal dinosaur. Critical measurements of 243 of the best preserved tracks have established the range of morphological variability within single trackways and provided limits of reliability (LOR) for using ichnospecies of bipedal dinosaur footprints to estimate biological species diversity. These LOR are an important method of evaluating previously described ichnospecies of dinosaur footprints in the Newark Supergroup of eastern North America. This evaluation suggests that earlier workers overinterpreted subtle differences among tracks. Of 7 ichnogenera and 23 ichnospecies of tridactyl saurischian dinosaur tracks described previously from the Newark Supergroup, only 3 ichnogenera and 8 ichnospecies can be consistently recognized. The rest fall into the range of morphological variability exhibited by these 8 ichnospecies. *Kayentapus hopii* from Arizona represents a ninth closely related valid ichnospecies.

INTRODUCTION

Recent quarrying by the Culpeper Stone Company, Inc. has uncovered footprints on a bedding surface in the Balls Bluff Siltstone about 130 feet below a previously discovered footprint-bearing surface described by Weems (1987). The geologic setting of the newly discovered surface is in many ways similar to the previously described surface. Both are on top of massive, calcareous cemented siltstone beds. The most abundant bedding features on these surfaces are ripple marks, footprints, and mudcracks recording the progressive drying of a mudflat along a lake margin. In both cases, after prolonged drying which hardened the mud, an influx of water into the lake probably caused it to expand and rapidly cover the exposed margin so that the footprints and other bedding features were preserved intact. Initially, only calcium carbonate was deposited on the footprint-bearing surfaces. In the case of the previously described layer, much of the carbonate was rolled into oolitic pellets which occur in patches across the track-bearing surface (Young and Edmundson, 1954; Carrozi, 1964). In the case of the newly discovered layer, the carbonate was broken but not rolled, so that fragments of stromatolites, tufa tubes, and conchostracan or molluscan bivalve shells were deposited in patches across the track-bearing surface. Two bone fragments, a parasuchian tooth, and fish scales have been found within the carbonate patches. The tracks and carbonate deposits on both track-bearing surfaces subsequently were covered by one to three feet of well laminated gray shale, representing lacustrine deposition. So far, fish scraps have not been found in the gray shale.

The prints in the upper layer were less distinct but relatively more diverse and numerous, being densely concentrated over much of the exposed surface. However, because much more of the lower layer has been exposed the total number of prints found on the lower layer (about 2,000) greatly exceeds the number found on the upper layer (about 830 in recognizable trackways). The lower layer, which includes numerous tracks of high quality, may be the most extensively exposed Triassic dinosaur trackway bedding plane in the world (compare to Gillette and Lockley, 1989).

CHALLENGES OF FOOTPRINT TAXONOMY

A good naturalist can use tracks and trackways of modern animals to estimate their abundance and diversity in areas where sitings are uncommon. In theory, this approach can be applied to prehistoric communities as well. A paleoichnologist should be able to extract much diverse information on terrestrial faunas from examination of tracksites on bedding planes. In practice, however, modern naturalists do not encounter two obstacles that commonly hinder paleoichnologists. The first obstacle is that extensive trackway exposures on bedding planes are rare. Usually a small area of a bedding plane with perhaps a few tracks is all that is found, and often these are on isolated blocks of rock, out of their original stratigraphic context. The Culpeper Stone Company, Inc. quarry represents a remarkable exception to this, because it exposes an unusually large surface of a lacustrine shoreline mudflat and looks much as it did only days after Triassic animals crossed it.

A second obstacle confronting paleoichnologists, especially pre-Cenozoic specialists, is that the nature and diversity of the animals that left tracks at a given site often are unknown. In a modern setting, naturalists have a good (perhaps perfect) knowledge of what animals exist in an area and what they look like. This information usually is lacking for animals that made fossil trackways. Thus paleoichnologists are compelled to use tracks as *prima facie* evidence rather than as secondary aids for estimating abundance and diversity of animals that are already known. Although footprints of an individual animal are preserved differently in different settings (depending on the speed and gait of the animal and the resistance and coherence of the substrate), if a finite list of candidate trackmakers is available then the creator of a particular track or trackway can be deduced with little ambiguity. But without such a master list, assigning isolated tracks and bits of trackways to specific animals becomes a much more daunting task. Therefore, it is scientifically enlightening to have an extensive series of well-preserved trackways from numerous individuals of a local population of dinosaurs at the Culpeper quarry. These trackways can be used to establish optimal range limits for the morphological variability for tracks of these individuals and provide comparative insights on tracks of other similar dinosaurs. Obviously, if tracks or trackways of poor clarity are to be considered, the ranges of variability would be even higher than established here.

Ranges were established for this assemblage by measuring standard dimensions of well preserved individual footprints repeatedly along each trackway (Table 1). Only the best footprints in each trackway (about 15% of the total available sample) were used for measurement. The relative proportions of tracks in each of these trackways are similar, but the average length of tracks in different trackways varies from 208 to 303 mm. While such differences in size might reflect differences at a species level, two trackways strongly suggest that this is not the case. The trackway with the largest known prints (303 mm) is paralleled closely by another trackway having prints 250 mm in length (Figure 1). Both trackways go south, turn east together, stop sequentially (with the larger trackmaker stopping six steps in front of the smaller trackmaker), start again, turn south again together, then cross over each other and diverge with the smaller trackmaker going southeast and the larger one southwest. As the smaller trackmaker crossed the trail of the larger trackmaker, it stepped on a print of the larger individual, demonstrating that it was travelling behind the larger animal. The size difference between these two animals (15-20%) is not far different from the normal degree of sexual dimorphism found in living crocodilians and ratite birds (10-20%). Thus it is reasonable to interpret these two trackways as representing a male and female walking together, with the male slightly in the lead. This evidence, in conjunction with a uniform size gradient of trackway prints in the 235 to 260 mm range, indicates that all but perhaps the smallest set of footprints were produced by a single population of a single species.

The impressed foot length (fl), foot width (fw), and the extension of the middle toe (te) were chosen as the basic parameters for measuring footprints of each animal's trackway (Figure 2a, 2b). Total toe length was not chosen as a parameter because the degree to which digit impressions do or do not merge together depends strongly on the animal's speed and the nature of the substrate. Digit divarication was difficult to measure consistently and is a very variable feature (Olsen and Baird, 1986), so it also was not used. The arithmetic mean per dimension for each individual was calculated, and these mean values used to calculate toe extension/foot width (te/fw) and basal foot length/foot width (fl-te)/fw) ratios (see Figure 2c for definitions). Each ratio and one standard deviation error bars were plotted on a linear scale graph with the ratios represented on the horizontal and the vertical axes, respectively (Figure 3). The dotted line

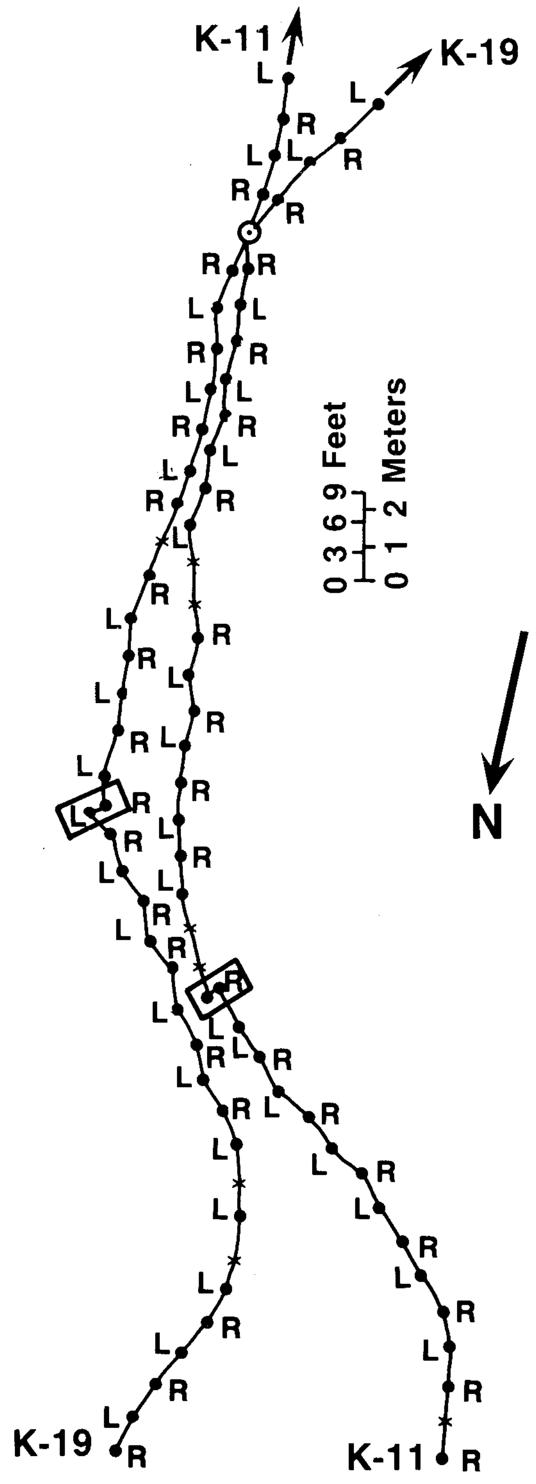

Figure 1. Map view of segments of trackways K-11 and K-19. The parallel behavior of the two trackmakers strongly suggests that they were walking together. Because one track of K-11 is impressed on one track of K-19, K-19 must have been in the lead. The foot of K-11 was about 250 mm long, the foot of K-19 was about 303 mm long, so K-19 was about 20% larger than K-11. The only alternative explanation was the K-11 was tracking or stalking K-19.

Table 1. Measurements (in mm) of 243 dinosaur footprints attributed to *Kayentapus minor* from the Culpeper Stone Company, Inc. quarry. See Figure 2 for term definitions. L = left foot, R = right foot.

Trackway	Foot length	Foot width	Toe extension		Foot length	Foot width	Toe extension	
K-1	239	186	101	L	239	187	87	R
K-1 averages	239	187	94					
K-2	250	205	85	L	245	180	93	R
	260	185	105	L	255	198	89	L
	263	197	110	R	248	202	101	R
	250	198	97	L	250	209	98	L
	260	200	96	R	245	198	84	R
	265	194	96	L	280	202	88	L
	257	190	99	R	238	208	100	L
	273	208	112	L	254	194	115	R
	262	210	98	L	251	199	97	R
	271	200	101	L	250	196	96	R
	233	208	94	L	266	204	99	R
	262	202	95	L	271	209	100	L
	259	176	120	R	255	203	101	L
	256	193	91	R	270	200	105	L
	242	201	96	R	268	200	106	L
	265	190	103	R	259	201	101	R
K-2 averages	258	198	99					
K-3	249	194	101	L	248	188	91	R
	244	180	106	L	240	172	101	L
	242	191	104	R	242	174	111	R
	241	194	94	R				
K-3 averages	244	185	101					
K-4	256	183	103	L	238	166	88	R
	237	180	84	L	246	178	97	L
	236	167	90	R	243	176	93	R
	245	176	94	L	239	172	97	R
	231	163	86	R	239	172	98	L
K-4 averages	241	173	93					
K-5	237	183	85	L	242	188	98	R
	234	190	94	R	231	186	94	L
	238	171	97	L	232	176	98	R
	237	165	98	L	230	178	98	R
	238	169	96	L	234	179	97	R
	244	174	104	L	222	178	92	R
K-5 averages	235	178	96					
K-6	215	158	96	L	208	172	85	L
	215	151	94	R	210	168	85	L
	200	155	75	R	202	165	82	L
K-6 averages	208	162	86					
K-7	247	177	96	L	256	176	99	R
	253	164	100	L	253	177	98	R
	256	172	100	L	241	182	96	R
	251	183	100	L	253	185	103	R

	253	170	96	L	246	176	96	R
	246	183	93	R	254	174	95	L
K-7 averages	251	177	98					
K-8	251	186	98	L	249	174	102	R
	251	181	95	L				
K-8 averages	250	180	98					
K-9	241	180	97	R	232	175	95	L
	241	172	99	R	240	171	101	R
	236	177	91	L	237	165	104	L
	233	178	90	R	242	174	103	R
	240	167	101	L	239	177	100	R
K-9 averages	238	174	98					
K-10	247	178	99	R	247	183	97	L
	256	181	103	R	235	185	98	L
	246	179	99	R	250	184	102	R
	238	191	98	L	244	183	98	R
	246	178	103	R	239	184	101	R
	235	186	95	L	243	182	99	L
	238	184	96	L	244	184	98	L
	251	182	105	R	244	174	97	L
	250	169	104	L	272	176	120	R
	249	173	116	L	253	176	110	R
	245	174	101	L	240	175	100	L
	247	170	95	R	238	156	112	L
	249	179	106	R				
K-10 averages	246	179	102					
K-11	241	184	93	R	254	171	100	L
	247	190	97	R	255	183	101	L
	251	186	98	R	258	186	99	L
	246	181	93	L	255	187	103	L
	246	180	97	R	251	191	91	R
	255	186	100	L	245	185	92	L
	255	181	102	L	256	195	112	L
	247	161	101	R	247	177	92	L
	246	199	100	R	244	190	91	R
	245	189	96	R	252	197	101	R
	253	196	109	R	252	190	104	L
	256	197	104	R	256	187	105	L
	254	186	96	L	258	179	101	L
K-11 averages	252	186	99					
K-12	245	172	86	R	252	196	104	L
	247	175	105	R	246	183	91	R
	248	186	112	L	242	177	112	R
	246	194	101	L	250	199	99	L
	247	188	99	L	249	182	92	R
	250	196	111	L	254	180	110	R
K-12 averages	248	186	102					
K-13	261	214	112	L	259	212	100	R
	259	214	102	L	260	209	106	R
	258	210	106	L	262	206	105	R
	255	210	101	L	262	209	102	R
	261	214	109	L	256	211	103	L

	255	214	105	R	265	207	104	R
	255	210	97	R	260	211	109	L
	270	212	109	L	266	208	106	R
	264	210	105	R	256	214	109	L
K-13 averages	260	211	107					
K-14	242	191	92	L	245	193	96	L
	234	188	85	R	245	190	99	L
	251	194	102	R	257	198	101	L
	250	196	99	L	251	189	101	L
	247	192	101	R	248	192	98	L
	257	188	108	R	244	194	88	L
K-14 averages	248	192	98					
K-15	241	188	113	L	235	195	99	L
	240	192	104	R	235	202	103	L
	221	186	85	R	240	192	106	R
	252	192	106	L	248	187	100	R
	255	192	105	L	247	198	110	R
K-15 averages	241	192	103					
K-16	240	177	95	R	256	177	99	L
	249	175	111	L	246	179	104	L
	251	182	108	R	250	176	101	R
	247	181	97	L	252	180	98	R
	255	175	111	L	250	182	104	R
	244	181	113	R	255	176	108	L
K-16 averages	250	178	104					
K-17	240	189	99	R	241	187	98	R
	231	175	89	L	239	190	98	R
	241	175	94	L	242	179	95	L
	242	186	95	L	242	189	92	R
	240	180	97	R	242	176	93	L
	236	188	91	R				
K-17 averages	240	183	95					
K-18	252	208	102	R	254	210	112	R
	254	204	112	L	253	212	102	R
	256	202	100	L				
K-18 averages	254	207	106					
K-19	309	212	118	R	312	206	114	R
	314	218	120	R	301	222	121	L
	303	214	111	L	303	219	117	L
	300	220	115	L	300	214	115	L
	294	204	115	R	300	220	110	L
	300	205	120	R	305	220	105	L
K-19 averages	303	215	115					
K-20	263	203	102	R	250	206	102	L
	255	193	102	L	245	200	106	R
	259	196	108	L	256	195	88	R
K-20 averages	255	199	101					

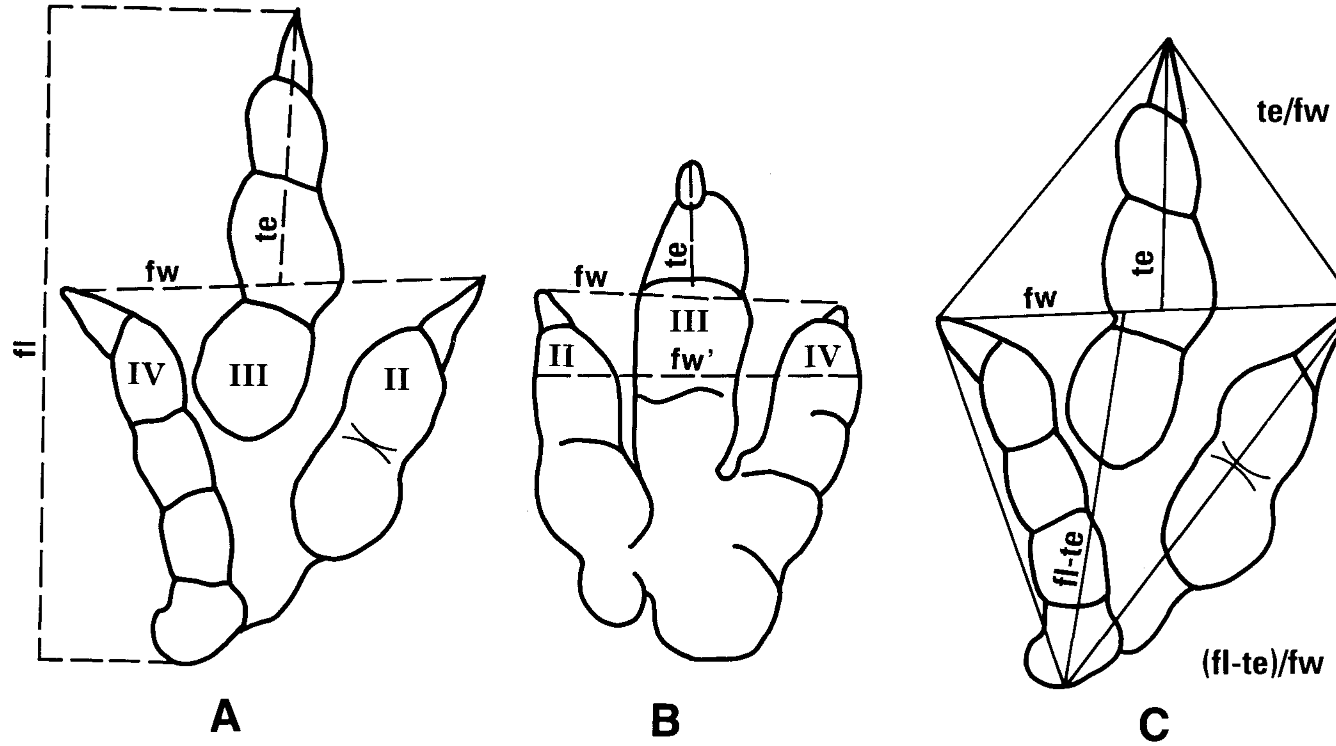

Figure 2. A. Outline drawing of a *Grallator*-like dinosaur footprint showing the parameters of the foot measured for this study. fl = greatest foot length from rear pad of digit IV to the tip of the claw of digit III, as measured along the axis of the foot; fw = greatest foot width; te = extension of digit III beyond a line drawn across the tips of digits II and IV, measured down the axis of digit III. B. Outline drawing of a *Eubrontes*-like footprint, showing method of measurement used when the width of the pads of digits II and IV are wider than the tips of the claws. fw' = point at which foot width is measured on this kind of track. te still is determined from a line drawn across the tips of digits II and IV (fw) as in case A. C. Outline drawing of a *Grallator*-like footprint showing the two ratios determined from the measured parameters. Because te and fl usually are not quite measured along the same line, fl-te is a close estimate of the line labelled fl-te rather than an exact measurement. These ratios basically define a footprint as two triangles, one facing anteriorly and one facing posteriorly.

enclosing the composited values represents the minimum morphological range expected within this well preserved single population of tridactyl bipedal dinosaur footprints. The field defined by these mean values and error bars constitutes the minimum inherent variability that reasonably may be expected within this population. If conditions of preservation were less favorable, the footprint measurements would have less reliability than found here.

The mean values of the Culpeper quarry trackways (shown by X's in Figure 4) vary from 0.50 to 0.58 for te/fw, and from 0.71 to 0.87 for (fl-te)/fw. Because these trackways yielded a considerable range of values, and because these values presumably represent a single biological population leaving prints made and preserved under exceptionally favorable circumstances, it is improbable that closely related and morphologically very similar biological species would leave trackways that could be consistently differentiated. As the variability documented here is a well supported minimum value for the variability that must be incorporated into the definition of a field-useful ichnospecies, it is therefore quite probable that closely related biological species with similar foot proportions could not be consistently differentiated. Forms with the same critical dimensions could be differentiated meaningfully only if they have other distinctive attributes (such as differences in the number of pads in the digits or demonstrably different digit proportions or shapes that cannot be attributed to substrate effects). This supports Baird's (1957) contention that ichnospecies correspond roughly to biological genera.

COMPARISONS WITH PREVIOUSLY DESCRIBED BIPEDAL NEWARK SUPERGROUP ICHNOSPECIES

Using these minimum limits of variability, the author visited the Pratt Museum at Amherst College and measured the critical dimensions of type specimens of most tridactyl bipedal saurischian ichnospecies in that collection. Only *Eubrontes, tuberosus, Eubrontes approximatus*, and *Grallator gracillis* were not measured from the type specimens. Corresponding ratios based on these types were plotted in the same manner as the Culpeper quarry prints (Figure 4) to permit reasonable comparison. Specimens not available for

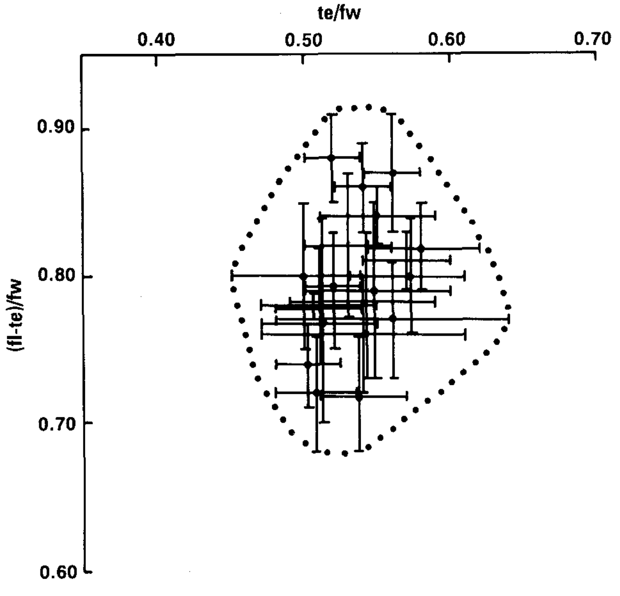

Figure 3. Diagram showing the mean ratio values for twenty trackways of *Kayentapus minor* in the Culpeper Stone Company, Inc. quarry. Vertical axis represents the ratio (fl-te)/fw, horizontal axis represents the ratio te/fw. Bar lines indicate one standard deviation from each mean value along each axis. The most common standard deviation for these values is 0.04. Note that the array is relatively homogeneous. A dotted line bounds the outer limits of the standard deviation bars and defines the area of typical ratios for footprints of this species. This bounding line is the same as that surrounding the *Kayentapus minor* field in Figure 4.

study at the Pratt Museum were extracted from the figures published in Hitchcock (1858, 1865) or Lull (1953). The values for *Kayentapus hopii*, checked by the author against the holotype material at University of California at Berkeley, are taken from Welles (1971). The resulting measurements are shown in Table 2, and the cumulative graph (Figure 4) suggests that many of these ichnospecies are so similar in critical dimensions that they cannot be differentiated reliably. Variations in foot and digit shape among those forms with similar critical dimensions fall within the limits of variability seen in the Culpeper Stone Company, Inc. quarry material. Using the field limits defined by the assemblage as a template, fields of comparable size and variability were circumscribed (solid lines) about comparably proportioned taxa to create more realistic estimates of the probable variability within single ichnospecies. Each of the defined fields has one or more existing names applied to it.

Two taxa, *"Apatichnus" minor* and *Stenonyx lateralis*, have proportions which fall within the field defined by the Culpeper prints (Figure 4). Although the type of *"A." minor* is near the lower size range of the Culpeper prints, another print labelled *"Apatichnus minor"* on Amherst College slab A.C. 25/1 has absolute dimensions very near the average of the Culpeper footprints (Figure 5). *Stenonyx*, in contrast, is a much smaller form. It is unrealistic to expect that fossil footprints exclusively represent adult individuals, so I suggest that *Stenonyx* represents a very young *"A." minor* rather than a separate ichnospecies of animal.

The three type tracks of *Grallator cursorius* are from a single trackway and made by a single individual. Obviously the track with the lowest (fl-te)/fw value is atypical, specifically because the back part of the foot did not impress into the mud as it did on the other two tracks. In general, as a result of variable locomotor styles, (fl-te)/fw values are more variable than te/fw values (see Figure 3). For example, running animals generally shift more weight to their toes than do walking animals. The variability observed here emphasizes the importance of establishing ichnotaxa on prints that are clear, do not indicate abnormal behavior (such as slipping) or abnormal anatomy (such as broken nails) and do not differ from closely related taxa simply by what parts of the foot were impressed (as in animals that can be seen to vary from plantigrade to digitigrade within single trackways).

Comparisons of prints assigned to the ichnogenera *Grallator* and *Anchisauripus* indicates that there is no compelling reason to retain the junior name *Anchisauripus*. A rearwardly rotated hallux (digit I), such as Lull claimed to be present in *Anchisauripus*, might seem like a good ichnogeneric character. But in no instance was such a digit obvious in the material that I examined. In the type slab of *A. sillimani* (the genotype), it is apparent on close examination that the rearwardly directed "digits" are actually segments of mudcracks radiating outward from the extremities of the footprints. This specimen is a counterslab, so that prints and mudcracks are represented in raised relief. The slender mudcrack fillings mostly have broken away, except where adjacent raised print impressions have provided additional bracing. This creates an illusion that mudcrack segments near prints represent "digit" impressions, but careful inspection shows that in every case the broken base of the extra "digits" continue outward to form typical polygonal mudcrack patterns. Although *Gigandipus caudatus* does clearly possess a moderately reduced and mesially rotated digit I, in no instance was there clear or convincing evidence that any of the small nicks and depressions scattered across *Anchisauripus* track-bearing surfaces represented toenail marks of a reduced, rearwardly rotated first digit. Therefore, because its defining character state cannot be demonstrated convincingly, the ichnospecies assigned to *Anchisauripus* are incorporated here into *Grallator* and *Eubrontes*.

The fields of three of the recognizably different *Grallator* ichnospecies almost perfectly match the proportions of four ichnospecies recently erected within the ichnogenus *Atreipus* by Olsen and Baird (1986). Although they tentatively recognized four ichnospecies of *Atreipus*, they noted that *A. metzneri* from Germany may well be conspecific with *A. milfordensis* from the Newark. The proportions from their composite drawings for these two ichnospecies of *Atreipus* (shown by asterisks on Figure 4) plot closely together and thus indicate that these two ichnospecies cannot be distinguished effectively. Although differences in the proportions of the remaining three Newark Supergroup ichnospecies of *Atreipus* are sufficient to merit separate recognition, the proportions of each correspond almost perfectly to the pro

Table 2. Measurements (mm) of type and reference specimens for selected ichnospecies of dinosaurs. * = measurements from published figures and not original specimens, underlining indicates a referred specimen other than holotype.

	Foot Length	Foot Width	Toe Extension	
Anchisauripus				
A. exsertus	210	118	76	A.C. 16/6
	214	115	80	"
	223	124	79	"
	209	116	77	"
A. hitchcocki	117	66	48	A.C. 56/1
A. minusculus	307	198	101	A.C. 16/1
	303	198	100	"
	327	208	116	A.C. 16/12
A. parallelus	167	80	56	A.C. 54/8
A. sillimani	147	65	55	A.C. 9/14
	175	75	65	"
	168	79	65	A.C. 51/14
	131	60	53	A.C. 4/1
	139	66	53	A.C. 36/19
A. tuberosus	175	100	56	A.C. 31/73
Anomoepus				
A. crassus	158*	140*	54*	(Lull, 1953)
A. curvatus	93*	72*	24.5*	(Hitchcock, 1865)
A. gracillimus	66*	62*	19*	(Lull, 1953)
A. intermedius	102*	88*	32*	(Lull, 1953)
	102	95	32	A.C. 48/1
	101	95	33	"
	105	94	35	"
	101	91	34	"
A. isodactylus	115*	100*	26*	(Lull, 1953)
A. minimus	54*	57*	20*	(Hitchcock, 1865)
A. scambus	92*	67*	24*	(Lull, 1953)
Anticheiropus				
A. pilulatus	481	400	230	A.C. 10/4
Apatichnus				
A. circumagens	74*	62*	24*	(Lull, 1953)
A. minor	221	155	90	A.C. 1/3
	245	180	98	A.C. 25/1
Atreipus				
A. acadianus	150*	85*	63*	(Olsen and Baird, 1986)
A. metzneri	80*	44*	26*	"
A. milfordensis	107*	58*	36*	"
A. sulcatus	119*	58*	38*	"
Eubrontes				
E. approximatus	380*	276*	128*	(Hitchcock, 1865)
E. divaricatus	355	265	121	A.C. 58/1 (unlabelled)
	354	276	117	"
	352	287	111	"
	400	323	130	A.C. 44/1
E. giganteus	440+	363	122+	A.C. 45/8
E. "giganteus"	380	250	107	A.C. 45/1
	378	254	116	"
	370	242	110	"

E. playtpus	280	200	85	A.C. 13/4
	272	199	75	"
	275	197	76	"
E. tuberatus	236*	146*	76*	(Lull, 1953)
Gigandipus				
G. caudatus	382	255	126	A.C. 9/9
	422	265	135	A.C. 9/10
	421	275	127	"
	418	266	140	"
Grallator				
G. cuneatus	116	72	52	A.C. 25/1
	110	66	47	"
	123	72	50	"
	103	65	42	"
	130	75	54	A.C. 17/1
	129	78	54	"
	126	72	54	"
	123*	73.5*	50*	(Hitchcock, 1858)
G. cursorius	70	34	33	A.C. 4/1
	78	32	34	"
	79	31	33	"
G. formosus	165	102	66	A.C. 3/1
	193	116	81	A.C. 25/1
G. gracilis	46*	24.5*	18*	(Hitchcock, 1865)
G. tenuis	64	38	29	A.C. 12/3
	65	36	29	"
	64	37	27	"
	66	38	28	"
Gregaripus				
G. bairdi	108	74	36	USNM 358651
	111	72	38	USNM 358652B
	110	71	35	USNM 358652D
	108	73	33	USNM 358660
	108	72	33	USNM 358659
Kayentapus				
K. hopii	340*	290*	127*	(Welles, 1971)
	355*	290*	120*	"
Otouphepus				
O. magnificus	161*	89*	52*	(Lull, 1953)
O. minor	82*	37*	32*	(Lull, 1953)
Stenonyx				
S. lateralis	29	21	12	A.C. 47/40

portions and absolute size of three ichnospecies of *Grallator* already represented in Figure 4. Moreover, it is suspicious that the nails of digits II and IV are rotated laterally in both of the proportionately equivalent ichnospecies *Grallator tenuis* and *Atreipus acadianus*, while digit IV seems to have an extra footpad in both of the proportionately equivalent ichnospecies *Grallator parallelus* and *Atreipus sulcatus*. Thus a serious question arises whether these new ichnospecies of *Atreipus* can be distinguished reliably from previously described ichnospeies of *Grallator*.

The most obvious distinction between *Atreipus* and *Grallator* rests, so to speak, on the manus prints present in *Atreipus*. However, the ichnogenotype for *Atreipus (A. milfordensis)* includes only a pes print, as does the type specimen for *A. sulcatus*, so the association of manus prints with these two species is based entirely on referred material. Rigorous definition of taxonomically useful trackway characteristics is weakened further by the fact that trackways of *Atreipus* are known to vary from bipedal to quadrupedal (Olsen and Baird, 1986), so the presence of manus prints cannot be considered to be a consistent characteristic of this taxon. So far, all manus prints associable with a *Grallator*-like pes have been like the manus prints described for *Atreipus*. Therefore, *Grallator* prints have been reclassified consis-

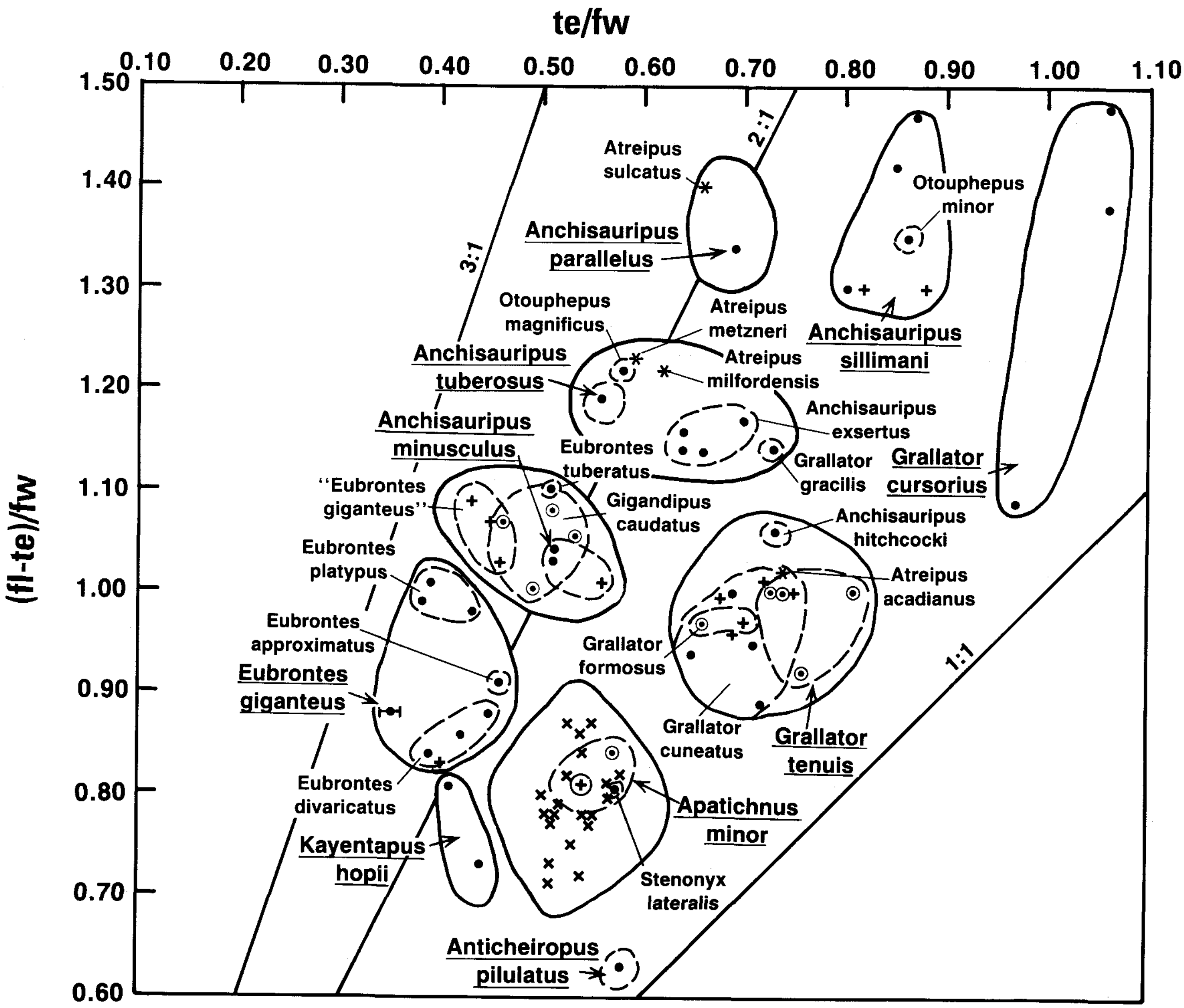

Figure 4. Graphic display of the foot measurement ratios in various dinosaur and dinosaur-like ichnospecies. x = mean values for trackways of *Kayentapus minor* measured in the Culpeper Stone Company, Inc. quarry, · = measurement on an individual print of a type specimen, + = measurement on an individual print of a referred specimen, * = values derived from the composite drawings of species of *Atreipus* taken from Olsen and Baird (1986). Circles drawn around symbols serve to cluster them as one form in areas when prints previously accewpted as representing single ichnotaxa have similar proportions. Ratio values indicate proportions where the toe extension and the rear of the foot are equally long (1:1), the toe extension is half of the length of the rear of the foot (2:1), and the toe extension is a third of the length of the rear of the foot (3:1). Note that all of these forms fall between ratios of 1:1 and 3:1. Dashed lines bound fields of measurements previously accepted as representing single ichnospecies. Solid lines represent fields accepted here as representing single ichnospecies of tridactyl dinosaurs. The proportions for *Gigandipus caudatus* are shown for comparison, but the bounding line is left dashed because it is a four-toed, rather than a three-toed, form. *Anticheiropus pilulatus* is shown by a dashed line because it may not be a dinosaur.

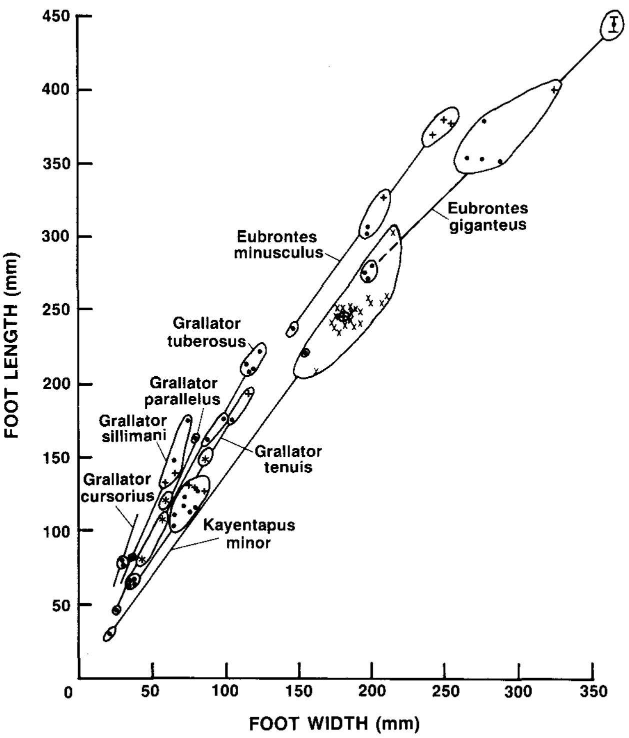

Figure 5. Proportions of various specimens of dinosaur footprints, with length (fl) plotted on the vertical axis and width (fw) plotted on the horizontal axis. x, ·, and + symbols have the same meaning as on Figure 4. Although the length and width of the largest known *Kayentapus minor* footprints are comparable to the length and width of the smallest known *Eubrontes giganteus* footprints, the te/fw ratios (Figure 4) and the growth slopes are distinctly different. Note that the putative species synonymized on Figure 4 are simply smaller or larger versions of tracks with the same basic proportions. Forms with te/fw ratios of 0.60 or more (*Grallator*) are generally smaller than forms with relatively shorter middle toes (*Eubrontes, Kayentapus*). This presumably relates to the fact that larger (and heavier) animals need to distribute their weight across all three middle toes to prevent frequent overstressing (and straining) of any one toe, whereas smaller animals are able to concentrate their weight on the middle toe without straining it. Concentrating weight and motion on an elongated middle toe allows an animal to cover ground more rapidly than it could if it had equal mass but shorter legs (= shorter stride length).

tently to *Atreipus* when manus impressions are found, while no distinctive manus prints different from the *Atreipus* type have been found to represent *Grallator*. Therefore, *Grallator* manus prints are effectively unknown by definition.

Olsen and Baird (1986) accepted that *Grallator* prints represent the feet of coelurosaurs, but they contended that the manus prints of *Atreipus* are "wrong" for coelurosaurs. This, however, is based partly upon the unconfirmed assumption that all *Grallator* prints were made by coelurosaurian dinosaurs. Moreover even if *Grallator* prints were made by coelurosaurian dinosaurs, it is by no means certain that they had hands similar to later coelurosaurs such as *Coelurus* of the Late Jurassic. Some later coelurosaurs, such as *Ornithominus*, retained hand proportions quite similar to those found in *Atreipus*. It is true that the manus prints of *Atreipus acadianus* indicate that the dominant digits in *Atreipus* were II, III, and IV. If, as some workers have assumed, the functional coelurosaur manus consisted of digits I, II, and III (Steel, 1970), then this could suggest that *Atreipus* was an ornithischian as Olsen and Baird (1986) have argued. But no compelling proof of this model has been presented, and it could be just as easily argued that the manus prints of *Atreipus* indicate that the functionally dominant coelurosaurian digits were II, III, and IV. Thus the manus characteristics of *Atreipus* do not clearly debar it from coelurosaurian association as Olsen and Baird suggest. As noted by Padian (1986), *Atreipus* may not require us to erect a new group unknown from osseous remains, but rather it may require us only to reconsider structural and functional assumptions about known groups.

When comparing only pes morphology, only two characteristics are reputed to distinguish *Atreipus* from *Grallator*. In *Atreipus* the creases between the footpads are broadly U-shaped, while in *Grallator* the creases are V-shaped. In digits II and III of *Atreipus* the metatarsal-phalangeal pads are often impressed, whereas in *Grallator* they generally are not (although the type of *Grallator parallelus* offers an obvious exception). While generally observable differences, these traits (and the presence or absence of handprints) all could be the difference between the same animals when walking (*Atreipus*) and running (*Grallator*) or when moving on substrates of different consistency. The only problem with this interpretation is the apparent persistence of *Grallator* and absence of *Atreipus* in higher Newark strata above the basal lava flows. This suggests that *Atreipus* disappeared before *Grallator*. However, this observation may be an artifact of sampling. Even if this distinction is valid, it is alternatively possible that the three least cursorial *Grallator*-like taxa became more cursorial through time, spending relatively less time on all fours. While this might serve as a basis for distinguishing successive ichnospecies (assuming that the later forms either *never* rested upon the forefeet or someday prove to have demonstrably different forefoot prints), the only known differences which can be cited are based upon negative evidence (absence of manus prints) related to assumed locomotor behavior rather than on physically discernable differences in foot morphology. Thus there is no useful, field-applicable basis for separating three previously described ichnospecies of *Grallator* from the recently described ichnospecies of *Atreipus*. For this reason, *Atreipus* is considered here to be a synonym of *Grallator* until more convincing evidence is presented that two ichnogenera can be usefully distinguished.

The compilation of previously described ichnotaxa, shown in Figure 4, suggests that 23 ichnospecies of bipedal saurischian dinosaurs described from the Newark Supergroup cannot be differentiated reliably into more than 8 ichnospecies. The ichnospecies name chosen for each field in Figure 4 is the oldest one which has been applied within it (shown in bold print). The clustering of these eight ichnospecies (and the closely related ichnospecies *Kayentapus hopii*) into genera is a somewhat subjective process, but I have chosen to cluster them into three ichnogenera conveniently representing small, medium, and large adult categories of related foot proportions (see Figure 5). It must be emphasized, however, that the following discussion emphasizes adult-size prints. Medium and large size forms can be represented by juveniles, with absolute dimensions comparable to the adult forms.

Consistently small taxa (under 230 mm total length at largest) are referred to the ichnogenus *Grallator*. These forms all have relatively high te/fw ratios (greater than 0.53) and (fl-te)/fw ratios (greater than 0.90). Based on foot proportions and relative tendency toward bipedality, there are three recognizable ichnospecies of moderately cursorial habit (*G. tuberosus*, *G. parallelus*, and *G. tenuis*) and two ichnospecies of strongly cursorial habit (*G. sillimani* and *G. cursorius*). *Grallator* probably represents a variety of primitive coelurosaurian dinosaurs.

Medium-sized forms are referred to the ichnogenus *Kayentapus*. The ichnogenotype of *Apatichnus* (*A. circumagens*) was applied to an ornithischian dinosaur footprint, while the referred ichnospecies *"A." minor* instead was a saurischian dinosaur (Weems, 1987). Therefore the name *"Apatichnus"* is inappropriate for the forms considered here. Although *Stenonyx* has nomenclatural priority over *Kayentapus*, its type is based on a very small individual that may not be much past hatchling stage and is only delicately impressed in the rock. While a remarkable specimen for its small size and delicate appearance, it seems inadvisable to use this faintly impressed form for an ichnogenotype. In the first place, the synonymy of *Stenonyx* with *"A." minor* cannot be strongly supported in the absence of intermediate growth stages between the presumed hatchling and adult size ranges. Also, if *Stenonyx lateralis* is synonymous with *"Apatichnus" minor*, the ichnospecies name *lateralis* would become a junior synonym of the ichnospecies name *minor*. Thus, adoption of the more recently defined ichnogenus *Kayentapus*, with its valid specific epithet, is preferred. *Kayentapus* is here considered to consist of two ichnospecies, *K. hopii* and *K. minor*. These animals possibly represent primitive carnivorous dinosaurs.

Large forms are retained in the ichnogenus *Eubrontes*, which has been the traditional name for large dinosaur footprints in the Newark. Two ichnospecies are recognizable, a broader-footed *E. giganteus* and a longer-footed *E. minusculis*. The suggested growth trend for *E. giganteus* (Figure 5) implies that the feet of this animal became proportionately somewhat wider as it grew larger (Figure 6), perhaps as a response to bearing its relatively huge size. Although some have argued that *Eubrontes* tracks were made by carnivorous theropod dinosaurs (Ostrom, 1972), the large size, social habits, and great abundance of these tracks suggest that most were more probably made by herbivorous prosauropod dinosaurs (Bock, 1952; Weems, 1987; Miller and others, 1989). However, as Weems (1987) points out, some theropod dinosaurs, as well as prosauropod dinosaurs, may have had foot proportions that fall within the critical dimensions presently defining the ichnogenus *Eubrontes*. Outline drawings are shown to the same scale in Figure 6 of the ichnospecies of *Eubrontes*, *Grallator*, and *Kayentapus* recognized here. The present re-evaluation of the forms listed in Lull (1953) and Olsen and Baird (1986) yields the following list of synonyms:

Eubrontes giganteus (= *Eubrontes approximatus* (type), = *Eubrontes divaricatus*, = *Eubrontes platypus*)

Eubrontes minusculus (= *Anchisauripus minusculus*, = *Eubrontes tuberatus*)

Grallator cursorius

Grallator parallelus (= *Anchisauripus parallelus*, = *Atreipus sulcatus*)

Grallator sillimani (= *Anchisauripus sillimani*, = *Otouphepus minor*)

Grallator tenuis (= *Anchisauripus hitchcocki*, = *Atreipus acadianus*, = *Grallator cuneatus*, = *Grallator formosus*)

Grallator tuberosus (= *Anchisauripus tuberosus*, = *Anchisauripus exsertus*, = *Atreipus metzneri*, = *Atreipus milfordensis*, = *Grallator gracilis*, = *Otouphepus magnificus*)

Kayentapus hoppi

Kayentapus minor (= *Apatichnus minor*, = *Stenonyx lateralis*)

THE STATUS OF OTHER BIPEDAL TRACKMAKERS IN THE NEWARK SUPERGROUP

Other kinds of bipedal to semibipedal tracks described from the Newark Supergroup deserve similar critical examination. These forms are *Sauropus*, *Selenichnus*, *Anticheiropus pilulatus*, *Hyphepus*, *Gigandipus*, *Anomoepus*, and *Gregaripus*. The type of *Sauropus*, a single manus print, has been shown by Olsen and Baird (1986) to be a *nomina vana*. Therefore it needs no further discussion. The two described ichnospecies of *Selenichnus* are unusual, being seemingly bidactyl rather than tridactyl. As envisioned, this animal hardly seem stable. It is curious that, in the type of *S. falcatus*, the missing to rudimentary digit II everywhere lies adjacent to or beneath the tail trace. Probably the tail trace obscured a much more robust digit II than the preserved imprints indicate. Additionally, this trackway could represent overprints or underprints, and not the actual surface on which this animal walked. In the case of *S. breviusculus* the entire print is rather obscure, and it is quite possible that the seemingly rudimentary digit II is simply not well impressed. Thus, the validity of *Selenichnus*, based upon presently known material, is doubtful.

Anticheiropus pilulatus is a bizarre and gigantic form described from a single, presumably pedal print. Perhaps it represents a bipedal dinosaur print, but if so its affinities are obscure. Whatever its true affinities, its proportions define a field quite different from those for ichnospecies of *Eubrontes*, *Grallator*, or *Kayentapus* (Figure 4). Therefore it is not

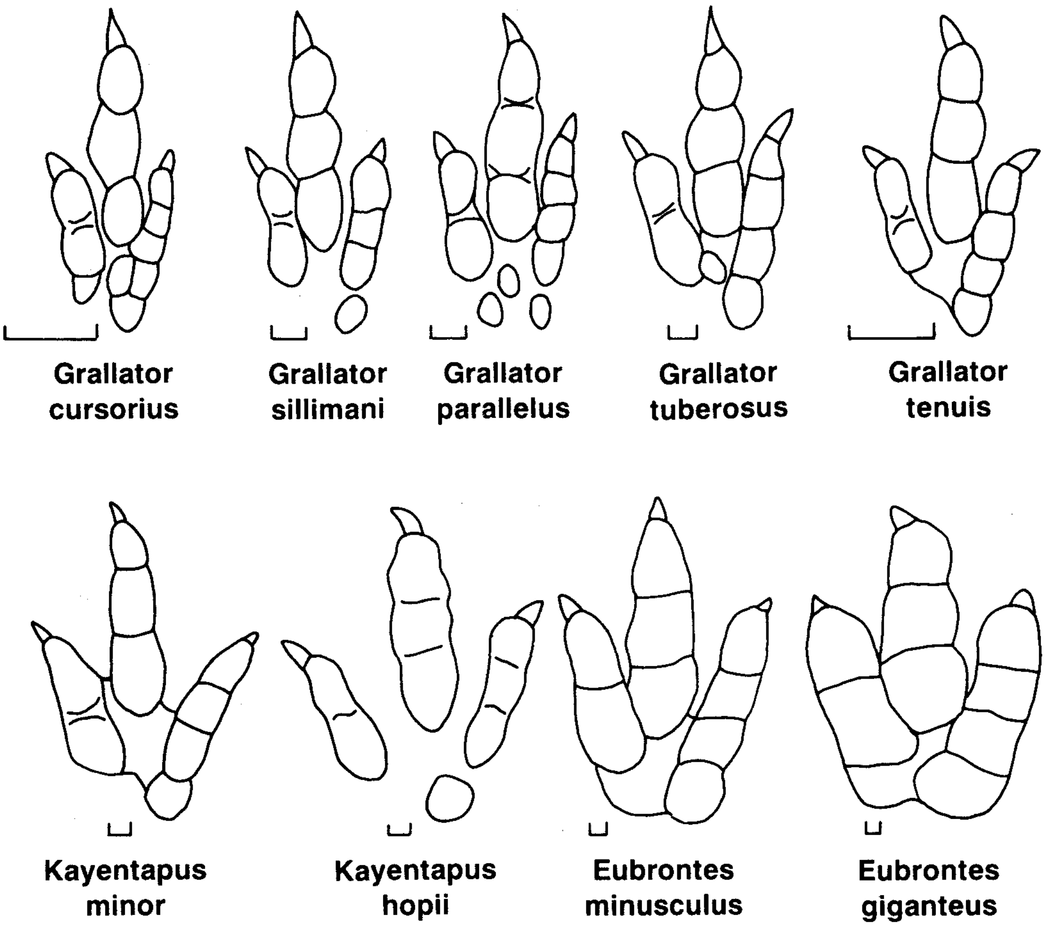

Figure 6. Outline drawings showing the relative proportions of the seven Newark Supergroup species of *Eubrontes*, *Grallator*, and *Kayentapus* recognized here, plus *Kayentapus hopii*. Bar scale equals 2 cm. Drawings were made from photographs of Amherst Museum specimens, except for *Kayentapus minor* (based on photographs of Culpeper quarry prints), *Kayentapus hopii* (adapted from Welles, 1971), *Grallator parallelus* (adapted from Lull, 1953), and *Eubrontes giganteus* (adapted from Hitchcock, 1865).

readily confused with any of those forms. *Hyphepus* is similarly an enigmatic form, though the type consists of numerous prints. The web-like film between the toes may have resulted from small animals walking on a thin algal mat (personal communication, Joseph Smoot, 1989). Thus this characteristic may not be taxonomically useful. Moreover, several measurements made from the type slab show a wide range of apparent proportions, suggesting that either the prints are extremely smudged or that more than one kind of animal made these prints. Most fall near the proportions of *Gigandipus*, and Lull (1953) thought that *Hyphepus* had a mesially rotated digit I similar to that of *Gigandipus*. Also, like *Gigandipus*, *Hyphepus* shows distinct tail drag marks. Perhaps most *Hyphepus* tracks represent juveniles of *Gigandipus*.

Adult *Gigandipus* have overall proportions comparable to *Eubrontes minusculus*. The two could not be distinguished if *Gigandipus* did not show the distinctive traits of an impressed mesially rotated digit I and tail drag marks. Because some of the trackways of *Eubrontes* are more deeply impressed than the type *Gigandipus* trackways, substrate differences cannot account for the observed differences. Therefore these two ichnogenera are considered here to be distinctive and valid unless it can be demonstrated by future discoveries that the observable differences are related to different behaviors in the same type of animal.

Detailed reanalysis of *Anomoepus* and *Gregaripus* is beyond the scope of this paper, but measurements of illustrations of prints of the different ichnospecies of *Anomoepus*, measurements on the type of *A. isodactylus*, and measurements on prints of *Gregaripus* are given in Table 2. *Gregaripus* has foot proportions comparable to *Eubrontes minusculus* and *Gigandipus caudatus*, but differs in its consistently much smaller size and apparently hoof-like foot which shows no indication of deep creases between the digits. Most *Anomoepus* have te/fw and (fl-te)/fw values lower than any recorded in Figure 4, though some do range as high as values recorded for *Eubrontes giganteus*. However, the small, delicate prints and toes of *Anomoepus* are not readily confused with the large prints and broad toes of *Eubrontes giganteus*.

CURRENT TAXONOMIC STATUS OF THE CULPEPER STONE COMPANY, INC. QUARRY FOOTPRINTS

In view of this taxonomic revision, the current taxonomy of the new and previously described footprints from the Culpeper quarry are summarized here. *Agrestipus hottoni*, *Gregaripus bairdi*, and *Eubrontes* sp., described by Weems (1987) from the upper track bearing surface, remain unchanged. The footprints described as *"Apatichnus" minor*, on the basis of the preceding taxonomic analysis, are now referable to the new combination *Kayentapus minor* without further change (Figure 7). Measurement of the middle toe extension to track width ratio for *Grallator?* yields a value (1.15 in USNM 358657) which is larger than that recorded from any well preserved material. This is probably because the tip of the toe dragged as the animal moved forward in deep mud, artificially elongating the apparent length of the toe print in USNM 358657. But besides the te/fw ratio, the speed estimates for this animal and the size of these prints also suggest that these tracks are referable to a long-toed ichnospecies. Their general proportions and morphology do not suggest anything other than *Grallator*, so these prints here are assigned to *Grallator cf. G. sillimani.*

The prints previously referred to *Anchisauripus parallelus* probably do not belong to that form. On reanalysis, the specimen on which that identification was based seems to include an impression of the metatarsal region, which gave the print an artificially long appearance. The best estimates for the te/fw ratio (0.57 to 0.62) and fl-te)/fw ratio (0.99 to 1.14) range between and slightly into the fields of both *Eubrontes minusculus* and *Grallator tuberosus*. However, considering its poor preservation, its size (smaller than any known *Eubrontes*), and geologic age (older than any previously reported *Eubrontes minusculus*), this trackway can be linked circumstantially to *Grallator tuberosus*. Therefore it is here termed *Grallator cf. G. tuberosus.*

On the lower track bearing surface, most footprints are referable to *Kayentapus minor*. A few small isolated tridactyl prints have te/fw proportions (0.84) typical of *Grallator sillimani* and thus are referred to that taxon. Elongate scratch marks which curve at the end probably represent claw marks left on the shallow lake bottom by swimming parasuchians (represented osteologically by an isolated tooth). Although too poorly preserved to be certain, these are tentatively referable to the ichnotaxon *Apatopus lineatus*. A fourth (quadrupedal) taxon, apparently a short-tailed barrel-bodied aetosaur similar to *Typothorax*, appears to represent a new ichnotaxon as yet unnamed.

ACKNOWLEDGEMENTS

I would like to thank the numerous individuals who at one time or another have aided me in exposing trackways, recording data, and mapping the footprints on the lower Culpeper quarry trackway bedding plane. Jonathon Bachman, Virginia Gonzalez, Robert Hodge, Frank Tseng, Eleanora Robbins, and Su-Chiu Weems deserve special mention for the exceptional amounts of time and effort they provided. The owners and operators of the Culpeper Stone Company, Inc. quarry, especially Gordon Willis, Fred Harris, and Robert Clore (who discovered the tracks on this surface), were exceptionally helpful and deserve commendation for their generous and public-spirited efforts on behalf of this study. Linda Thomas, Walter Coombs, and Margery Coombs provided valuable insights, assistance, and hospitality during my visit to the marvelous and invaluable Pratt Museum collections of dinosaur footprints at Amherst College. Finally, I wish to thank Ronald Litwin and Glen Kuban for their thorough and insightful reviews of this paper.

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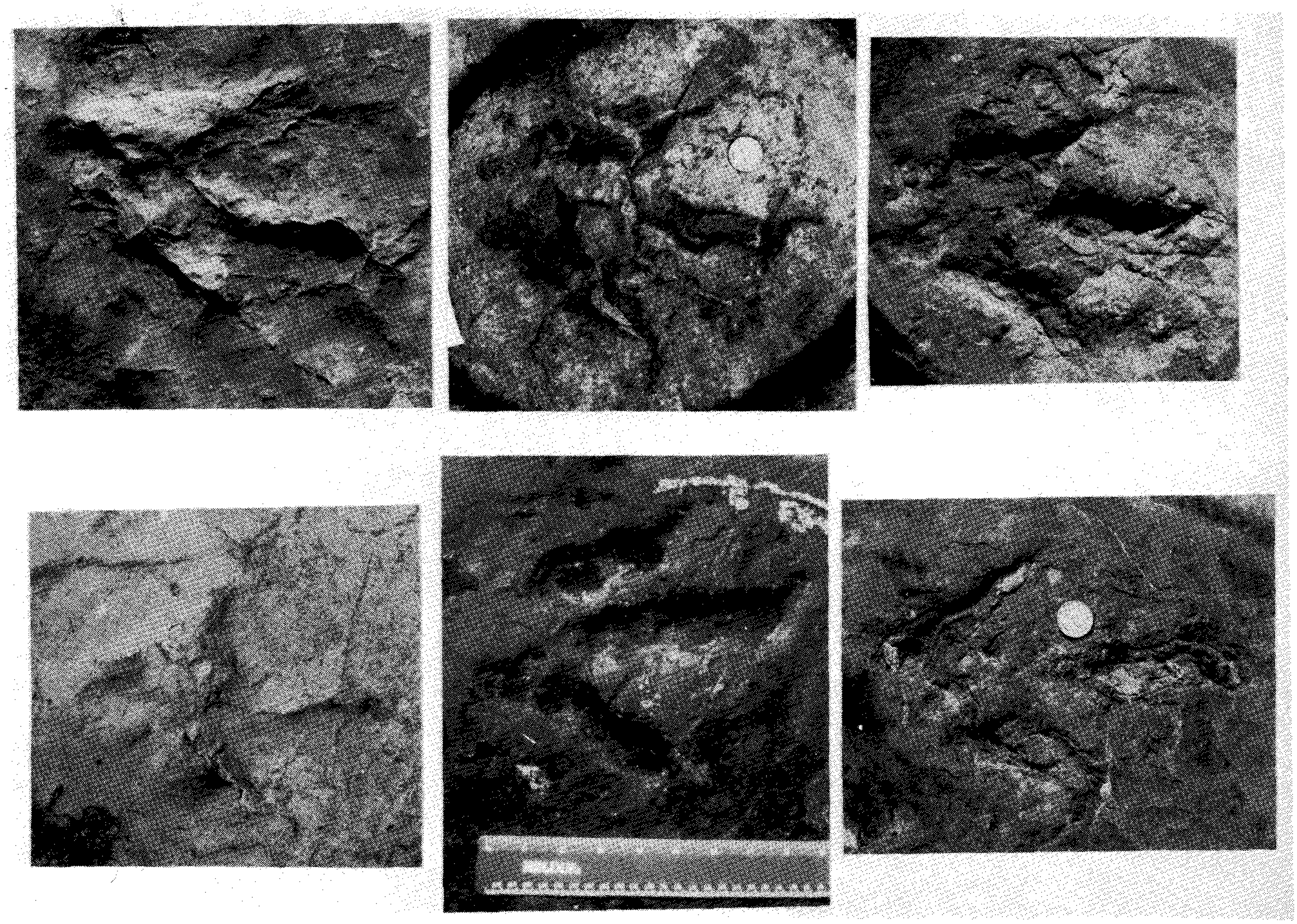

Figure 7. Photographs of representative footprints from six trackways of *Kayentapus minor* exposed in the Culpeper Stone Company, Inc. quarry. Upper left — right footprint from trackway K6 (average footprint length 208 mm). Upper right — left footprint from trackway K10 (average footprint length 246 mm, U.S. quarter for scale). Middle left — right footprint from trackway K11 (average footprint length 252 mm, U.S. quarter for scale). Middle right — right footprint from trackway K17 (average footprint length 240 mm, English-metric ruler for scale; picture courtesy of Glen J. Kuban). Lower left — left footprint from trackway K19 (average footprint length 303 mm). Lower right — left footprint from trackway K20 (average footprint length 255 mm).

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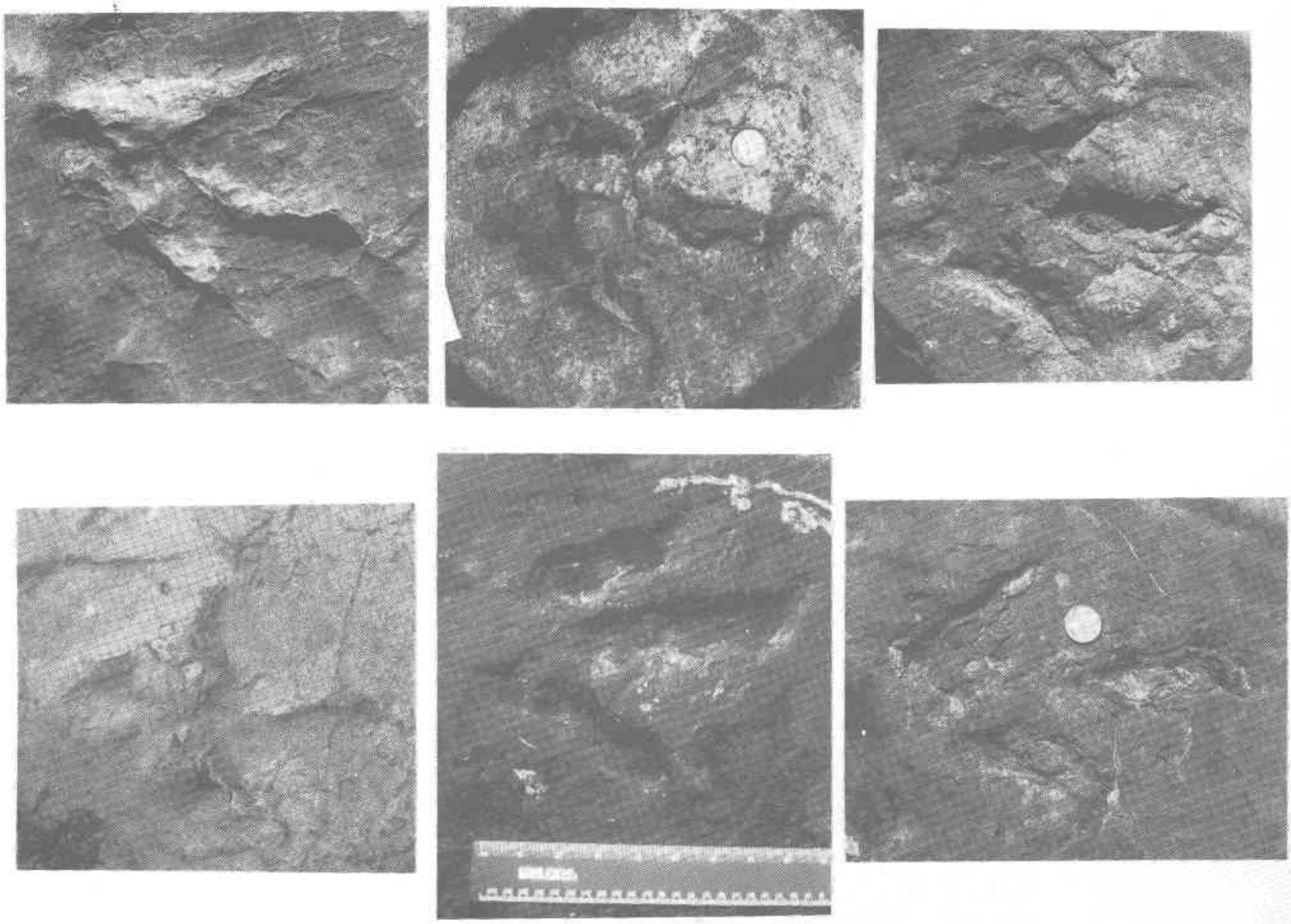

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GEOLOGY OF THE KYANITE DEPOSITS AT WILLIS MOUNTAIN, VIRGINIA

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INTRODUCTION

The kyanite deposit at Willis Mountain is located on the Willis Mountain 7.5-minute quadrangle in Buckingham County in the central Virginia Piedmont (Figure 1). This is the largest known kyanite deposit in the United States. Reported by Watson as early as 1908, the economic significance of this deposit was not realized until the early 1920s, after Joel H. Watkins discovered kyanite in the Baker Mountain area of Prince Edward County, Virginia. Early attempts to mine kyanite were unsuccessful due to a lack of a stable market. In early 1945 the Kyanite Mining Corporation acquired the Baker Mountain property and in 1948 expanded its operation to include the kyanite deposits at Willis Mountain. The Kyanite Mining Corporation has been in continuous operation since that time. At present all of the kyanite production in the United States comes from this operation in the Willis Mountain area. The Willis Mountain deposit is one of several occurrences of lenticular kyanite quartzite in an area approximately 30 miles long named the kyanite belt of Virginia by Jonas (1932). This area was renamed the Farmville district by Espenshade and Potter (1960).

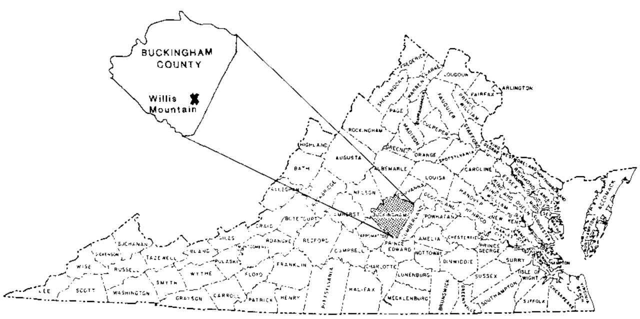

Figure 1. Map showing the location of the Willis Mountain kyanite deposit.

The bulk of the rocks in the Willis Mountain area are metavolcanic and are assigned to the Cambrian-age, Chopawamsic Formation. The Chopawamsic Formation is unconformably overlain by Ordovician-age schist and slates of the Arvonia Formation which include the kyanite-bearing rocks at Willis Mountain (Marr, 1981). The rocks of the Arvonia Formation lie in northeast trending belts that have a regional penetrative foliation that strikes northeast-southwest and dips to the southeast (Figure 2). Sedimentary rocks of Mesozoic age are located in the southeastern part of the Willis Mountain quadrangle within the Farmville basin.

The kyanite deposits at Willis Mountain formed as a result of a combination of processes that included original deposition of clastic and volcaniclastic sediments and subsequent alteration by metamorphism and later hydrothermal fluids. The deposits are closely related to the Chopawamsic-Arvonia Formation boundary and correlate with kyanite-bearing quartz-mica schists in the Arvonia Formation.

STRATIGRAPHY

CAMBRIAN-AGE ROCKS

Chopawamsic Formation

The Chopawamsic Formation was named for exposures along Chopawamsic Creek in northern Virginia by Southwick, Reed and Mixon (1971). The formation was extended into north-central Virginia by Higgins and others (1973), Pavlides and others (1974), and Conley and Johnson (1975). The Chopawamsic Formation was recognized in central Virginia by Conley (1978), and extended into the Willis Mountain area by Conley and Marr (1979, 1980), and Marr (1980A, 1980B).

The Chopawamsic Formation is represented by a bimodal volcanic rock suite with strong tholeiitic island-arc and weaker calc-alkaline affinities. In the Willis Mountain area the Chopawamsic is composed of a lower and an upper unit. The lower unit consists of interlayered chlorite schists, biotite metagraywackes and metabasalts with thin interlayers of mica phyllites and quartzite. The contact between the lower and the upper unit is gradational. The upper unit is composed of a sequence of felsic and mafic metavolcanic rocks and intercalated metasediments consisting of biotite gneiss, amphibole gneiss, rhyodacites, talc-tremolite schists, and ferruginous quartzites. The Chopawamsic Formation is considered to be Cambrian in age based on discordant radiometric zircon dates (Higgins and others, 1971)

ORDOVICIAN-AGE ROCKS

Arvonia Formation

The Arvonia Formation was named by Watson and Powell (1911) for exposures in the slate quarries at Arvonia, Virginia (Figure 2). The Arvonia Formation unconformably overlies the Chopawamsic Formation (Tabor, 1913). As recognized in the Willis Mountain area, the Arvonia formation consists of a basal, locally discontinuous, quartz-mica conglomerate and quartz-mica schist with interlayered mi-

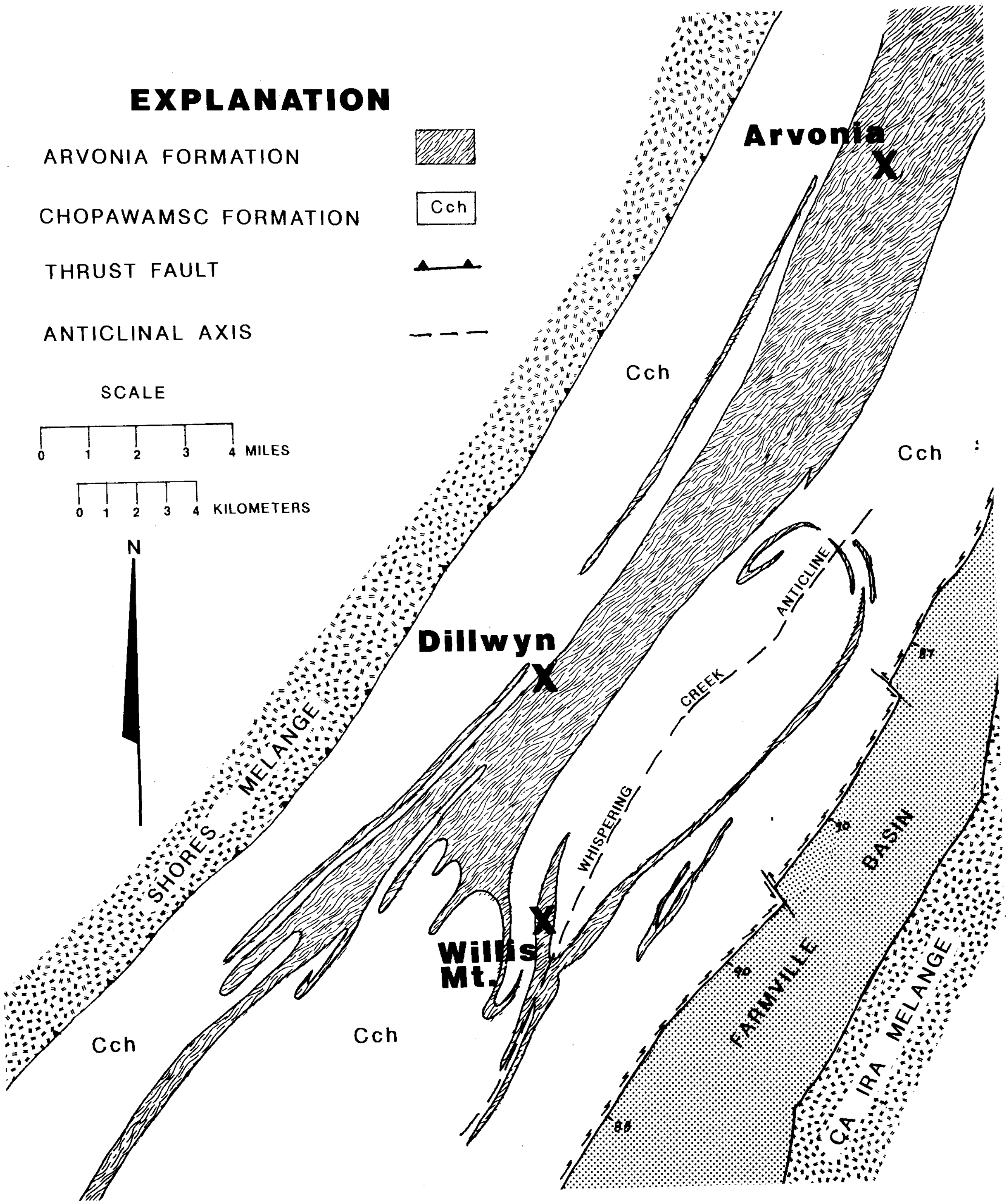

Figure 2. Generalized geologic map of the Willis Mountain area.

caceous quartzite. This interlayered interval is overlain by a moderately persistent, banded quartzite which is in turn overlain by a thick interval of porphyroblastic, garnet-mica-graphite schist. The Arvonia Formation also includes the kyanite-schists and conglomerates located on Willis Mountain. These kyanite-bearing quartz-mica schists and conglomerates were correlated with the basal units of the Arvonia Formation by Conley and Marr (1980). At Willis Mountain kyanite constitutes as much as 30% of the rock. It occurs as stringers and lenses within schist beds at Willis Mountain and at Arvonia it occurs as disseminated blades in the quartz-mica conglomerate of the basal Arvonia Formation (Evans and Marr, 1988). Sillimanite is also found in the conglomerate at both Willis Mountain and at Arvonia as fibrous prismatic crystals.

At Willis Mountain and at Woods Mountain the kyanite schist exhibits primary sedimentary structures. These include: repeated pairs of wedge-shaped quartzite and metapelite interlayers, conglomerates, fining-upward sequences, channel-fillings and both large-scale and small-scale cross-beds (Conley and Marr, 1980).

The rocks of the Arvonia Formation are considered to be Middle to Late Ordovician in age based on fossils identified at Arvonia, Virginia. Fossils that have been identified include: brachiopods, bryozoans, crinoids, pelecypods and trilobites (Darton, 1892; Dale, 1906; Watson and Powell, 1911; Smith, Milici and Greenburg, 1964; Brown, 1969; and Tillman, 1970). The slates at Arvonia have been dated at 300 m.y. using the whole-rock K-Ar method (Harper, and others, 1973). This date does not correspond to any known orogenic event affecting the rocks of the Virginia Piedmont and probably represents a time of cooling following a metamorphic event when the rocks formed a closed K-Ar system (Hadley, 1964).

JURASSIC-AGE ROCKS

Diabase Dikes

Diabase dikes of Jurassic-age intrude all crystalline rocks of the area, as well as, the Triassic-age sediments in the Farmville Basin. The diabase is dark-gray to black, fine- to medium-grained and has an ophitic texture. One of these dikes intrudes the kyanite schist at Willis Mountain near the southern end of the quarry.

STRUCTURAL CONSIDERATIONS

The rocks in the Willis Mountain area record four distinct periods of folding, one of which is found only within the Chopawamsic Formation which preceded deposition of the rocks of the Arvonia Formation. Major structural features present include the Whispering Creek anticline, synclinal infolds of Arvonia Formation rocks, several small-scale shear zones associated with tightly folded rocks. The Farmville basin was formed by normal faulting following the compressional event that produced the folds in both the Chopawamsic and Arvonia Formations. See Marr (1980A) and (1980B) for more complete structural discussion.

FOLDS

Isoclinal, intrafolial, rootless, F1 fold hinges can be observed in outcrop on the limbs of larger F2 folds. These F1 folds were only observed within the rocks of the Chopawamsic Formation. This same relationship was described between the folded rocks of the Chopawamsic and Quantico formations in northern Virginia by Pavlides (1973).

F2 folds include tight, isoclinal synclines and broader, more open anticlines. These folds generally strike to the northeast and are overturned to the northwest. S2 penetrative foliation is seen in all Paleozoic rocks of the area and is best developed in the rocks of the Arvonia Formation.

F3 folds are recognizeable at map scale where the penetrative S2 foliation is wrapped around F3 structures.

F4 Folds are also recognizeable at map scale where F3 folds have been warped by northeast-trending F4 structures.

FAULT

A fault zone bounds the Farmville basin on its western side. This fault is a high-angle normal fault that strikes northeast and dips to the southeast. The fault consists of fine-grained siliceous mylonite and extensively brecciated and silica-cemented cataclastic rock.

SHEAR ZONES

There are several narrow, discontinuous shear zones developed in the rocks of the area. These zones are developed along the flanks of major folds and are believed to be genetically related to the folding mechanism. These shear zones are particularly well developed along the flanks of the Arvonia Formation.

MELANGE ZONES

The lower unit of the Chopawamsic Formation is bounded along its western side by a melange zone consisting of quartz-feldspar metadiamictite that contains exotic blocks of mafic and ultramafic material. This melange occurrence is along strike to the northeast with the Shores Complex as described by Brown, (1986). This melange might also correlate with melange described in northern Virginia by Drake (1986) and Pavlides (1989). Subsurface reflection profiling across the central Virginia Piedmont indicates that the Shores Complex is bounded on the south-east side by an east-dipping low-angle thrust fault (Glover and Costain, 1982; Wehr and Glover, 1985).

A second previously unreported melange unit bounds the Farmville basin along its eastern boundary. This melange is informally named the Ca Ira melange for exposures in Rock Creek and other northwest trending drainages along the east side of the Willis River at Ca Ira, Virginia. This melange unit

REFERENCE	MODEL	DISCUSSION
Espenshade and Potter, 1960	1. Metamorphosed sedimentary rock.	Does not account for evidence of hydrothermal activity.
	2. Introduction of alumina into existing sediments by volcanism.	Rejected due to difficulty in introducing alumina into restricted beds.
	3. Leaching and/or replacement of sediments due to volcanic activity.	Leaching process would also remove alumina. No evidence of replacement textures.
Good, 1981	4. Deposits due entirely to volcanic activity.	Does not account for preserved sedimentary structures.
Marr, 1990	5. Combination process involving deposition of originally aluminous sediments, followed by hydrothermal leaching and volcanic alteration.	Accounts for presence of primary structures as well as evidence of hydrothermal activity.

Figure 3. Models proposed for genesis of the kyanite deposit at Willis Mountain, Virginia.

is classified as block-in-argillite and consists of chaotically-deformed arkosic metaconglomerate, metagraywacke conglomerate, mafic and felsic metavolcanic rocks, and slabs of ultramafic material (ophiolite?). The arkosic and graywacke metaconglomerate contains material consisting of lithic fragments of quartz, quartzite, mica schist, granite, amphibolite and ultramafic blocks in an metamorphosed arkosic to graywacke matrix. This melange unit lies immediately east of the unmetamorphosed fanglomerate and maroon, shaley mudstones of the Farmville basin. The western edge of the Ca Ira melange correlates with the Spotsylvania lineament an aeromagnetic and aeroradiometric anomaly that also marks the eastern limit of the Chopawamsic Formation. Seismic reflection profiling by Harris, de Witt and Bayer (1985) indicates that this anomaly represents an east-dipping, low-angle, thrust fault (Neushal (1970) and Marr (1985).

These two melange units effectively bind the Chopawamsic Formation on both its western and eastern sides. This configuration combined with the two east-dipping reflection profiles greatly increases the probability that the Chopawamsic block is part of an exotic eastern terrane transported to the west.

ORIGIN OF THE WILLIS MOUNTAIN KYANITE DEPOSIT

There are four previously proposed models dealing with the genesis of economic kyanite deposits found at Willis Mountain (Figure 3). Espenshade and Potter (1960) discussed three different models. These models included: 1. kyanite deposits due to the metamorphism of originally aluminous sediments, 2. deposits that resulted from the introduction of alumina into sedimentary sandstone beds, and, 3. deposits that were the result of replacement associated with volcanic processes. A fourth model has been mentioned by Good (1981), who believed that the Willis Mountain kyanite deposits were the result of volcanogenic deposition associated with fumarolic activity. This paper proposes a fifth model (Figure 3), that the genesis of the kyanite deposits at Willis Mountain involved a combination of processes including original sedimentary deposition and metamorphism followed by later hydrothermal alteration by fumarolic volcanogenic processes.

Espenshade and Potter (1960) and Bennett (1961) felt that the kyanite deposits at Willis Mountain were the result of the regional metamorphism of aluminous sediments. Their discussion centered around the occurrence of the kyanite rocks as persistent layers with the distribution patterns of stratigraphic units and as restricted stratigraphic markers within sequences of metamorphosed sedimentary and volcanic rocks. Espenshade and Potter (1960) also cited the absence of tourmaline associated with the kyanite deposits at Willis Mountain as evidence for a lack of hydrothermal alteration. Their argument was that these features were characteristic of metamorphosed sedimentary rock. They stated that the deposits have either been formed from sandy sediments containing clay or bauxite that have been folded and metamorphosed to their present state, or they have originated by selective replacement of certain beds, mainly sandstone. The second option was discarded as the introduction of aluminum into porous sandstone beds before or during metamorphism did not seem probable.

Good (1981) proposed that the sulfide occurrences in the Willis Mountain area formed in a back-arc basin by hot brines or fumaroles in distal volcanic fractures . He expanded this concept to include the kyanite deposits in the area. His evidence for this included: (1) the occurrence of kyanite associated with gossan of the Chopawamsic Formation; (2) the widespread occurrence of disseminated pyrite within the kyanite schists at both Willis and Woods mountains; (3) the occurrence of pipe-like features containing kaolinite and dickite clays and vein quartz within kyanite schists at Willis Mountain; (4) the occurrence of fuchsite (chromiun-bearing mica) associated with the kyanite schists; and (5) the presence of trace amounts of topaz in the kyanite schists in the Willis Mountain area.

Conley and Marr (1980) and Marr (1980a and 1980b) correlated the kyanite schists at Willis Mountain with the quartz-mica schists in the basal portion of the Arvonia Formation. This correlation was based on similar stratigraphic sequences and the presence of preserved primary sedimentary structures. The internal stratigraphy at Willis Mountain consists of a lower kyanite-quartz-mica schist and an upper unit of kyanite-quartz schist overlain by a restricted occurrence of graphitic metapelite. This stratigraphy at Willis Mountain matches the internal stratigraphy of the Arvonia Formation at its type locality.

The kyanite schist contains preserved primary structures consisting of wedge-shaped sedimentary packages composed of quartzite and quartzose kyanite couplets. The basal beds of many of these packages contain conglomerates that grade upward into quartzite and terminate at the top as a layer of almost pure quartzite. These features are interpreted as representing originally deposited fining-upward sequences. Each sequence was originally composed of a basal quartz gravel or coarse quartz sand that fines upward into silt and clay. Each package is truncated by the next overlying package. There are small-scale cross-beds in some packages. Channel fill structures truncate some of the cross-beds. All of these features are considered as evidence of original sedimentary deposition for the kyanite-quartz schists at Willis Mountain.

Early Paleozoic metamorphism of the rocks in the Willis Mountain area reached the upper amphibolite facies of medium- to high- grade regional dynamothermal metamorphism and imposed a regional foliation on all the rocks of the area. At this time the clay portion of the sedimentary sequence at Willis Mountain was converted to kyanite. Metamorphism was followed by late Paleozoic thrusting which produced the linear configuration of rock units shown in Figure 2.

Hydrothermal volcanogenic activity is also present in the rocks at Willis Mountain as evidenced by: (1) the presence of disseminated pyrite within the kyanite schists; (2) the presence of fuschite, and topaz as accessory minerals in the kyanite schists; and (3) the presence of tourmaline-quartz pegmatites which are abundant throughout the Willis Mountain area

From the available evidence it appears that the kyanite deposits at Willis Mountain are the result of a combination of processes. These processes included original sedimentary deposition and subsequent alteration by metamorphism and later hydrothermal fluids.

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KARST ASSOCIATED MINERAL DEPOSITS IN VIRGINIA

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ABSTRACT

Karst areas are typified by sinkholes, caves, and pinnacled bedrock that are formed by the dissolution of carbonate or evaporite rocks. Metalliferous and industrial minerals, rocks, and ores, associated with Virginia karst terrains, can be grouped in four types of deposits: residual concentrates, freshwater carbonate precipitates, efflorescent deposits, and hydrothermal deposits in karst induced porosity. Residual concentrates form or accumulate during karstic processes and include: barite, bauxite, kaolinitic clay, iron, lead, manganese, and zinc ores. Freshwater carbonate precipitates are deposited from carbonate-rich groundwater in caves or downstream from diffuse groundwater or spring inputs into streams and include: cave onyx and travertine-marl (stream) deposits. Efflorescent minerals accumulate in caves by migrating pore water: saltpetre. Hydrothermal mineralization in karstic porosity includes lead and zinc ores and probably Iceland spar.

INTRODUCTION

The term "karst" refers to terrain characterized by solution of bedrock, underground drainage, and distinctive land forms and features such as sinkholes, caves, and pinnacled bedrock. Karst is generally a type of erosional topography and develops on carbonate and evaporite rocks. Carbonate rocks are found in three of the five physiographic provinces of Virginia. The Valley and Ridge physiographic province contains the majority of the karst. Marble in the Piedmont and partially indurated shelly sands of the Coastal Plain physiographic provinces have minor karst development.

Metalliferous and industrial minerals, rocks, and ores associated with karst can be grouped into four types of deposits: residual concentrates, freshwater carbonate precipitates, efflorescent deposits, and hydrothermal deposits in karst induced porosity.

RESIDUAL CONCENTRATES

Residual deposits are comprised of accumulations of impurities from the carbonate rocks. Most of these impurities undergo some alteration or dissolution and precipitation during karstification of the carbonate host rock. Residual deposits include concentrations of iron and manganese, lead and zinc, barite, and bauxite and kaolinitic clay (Figure 1). The ease with which these deposits can be mechanically excavated and their concentrated nature has made them desirable economic targets.

Iron and manganese ores commonly are found in similar stratigraphic positions and contain features indicative of precipitation during karstification. The "Oriskany" and "shallow residual" iron deposits are karst associated and were mined as early as 1760. In the Oriskany (Ridgeley Sandstone) deposits, "Characteristically the ore is found replacing the upper pure limestone of the Helderberg" (Gooch, 1954, p. 3). Shallow residual ores are found associated with the Shady Dolomite, especially in the Pulaski-Smyth Limonite District (Gooch, 1954) where the ore is associated with secondary zinc ores (Currier, 1935).

The three manganese mining districts of Gooch (1955, p. 1), "Ridge and Valley," "Blue Ridge," and "Piedmont", have karst associated deposits. Manganese was produced in Virginia as early as 1832. In the Ridge and Valley district, karst manganese is concentrated in the residuum of the Helderberg limestone. Karst manganese in the Blue Ridge district is associated with the Shady (Tomstown) Dolomite. In the Piedmont district, karst manganese deposits are associated with the Mt. Athos marbles. Most of Virginia's production of manganese has been from Augusta, Smyth, Frederick, Bland, and Wythe Counties (Figure 1).

Lead and zinc have been mined as residual concentrates in Wythe and Pulaski Counties of Virginia (Figure 1). Lead was mined as early as 1750, while zinc was first mined in 1879. Cerussite, carbonate of lead, was not commercially mined until the late 1700s or early 1800s (Currier, 1935). Oxidized zinc ore, comprised of calamine and smithsonite, was referred to as "soft ore" and is best known from the Bertha zinc district (Case, 1894; Currier, 1935). Oxidized ores occurred as "masses and sheet-like bodies in the residual clays derived from Shady dolomite and as incrustations upon or secondary seams slightly penetrating the dolomite pinnacles" (Currier, 1935, p. 77).

Most of the barite production in Virginia is from residual deposits (Figure 1; Edmundson, 1936). Residual barite was mined from the Beekmantown and Conococheague formations in Botetourt County as early as 1850; from the Elbrook Formation in Roanoke County; from the Beekmantown Formation in Russell, Smyth, and Tazewell Counties (Watson, 1907; Edmundson, 1938).

The bauxite deposits of Virginia are associated with kaolin and represent sinkhole fillings, although there has been a difference of opinion as to whether the bauxite has formed from on site weathering products (Knechtel, 1963) or transported material (Bridge, 1950; Clarke, 1987). A small amount of bauxite was mined in 1915 at the Houston Manganese mine, associated with the Shady (Tomstown) Dolomite, in Botetourt County, Virginia (Figure 1; Warren and others, 1965). The remainder of the bauxite was produced from the Spottswood District, associated with the Beekmantown For-

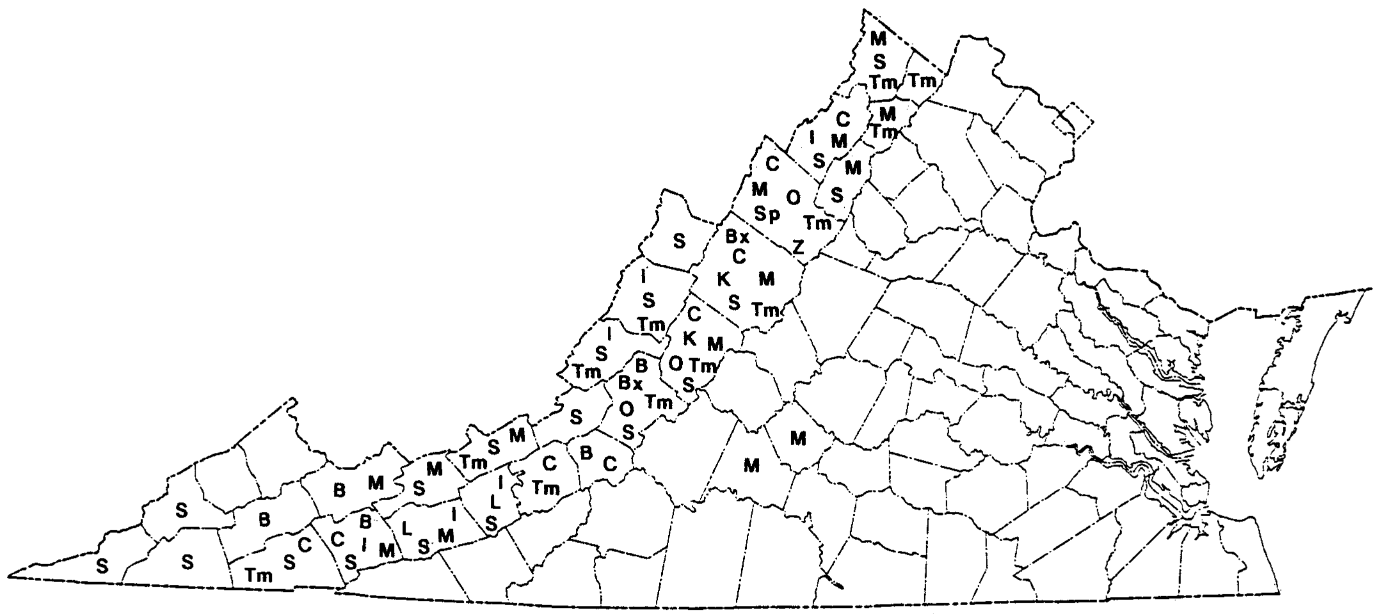

Figure 1. Counties in which karst associated mineral deposits were mined. Residual concentrates include iron (I), manganese (M), lead and zinc (L), barite (B), bauxite (Bx), clay (C), and refractory clay (K). Freshwater carbonate precipitates include stream deposited travertine-marl (Tm) and cave onyx (O). Efflorescent deposits are represented by saltpetre (S). Hydrothermal deposits associated with paleokarst include lead and zinc (Z) and probably Iceland spar (Sp).

mation, in Augusta County from 1940 to 1946 (Figure 1; Warren and others, 1965).

Many of the residual clays from limestone are red and plastic and have been mined for brick or tile manufacture in Augusta, Montgomery, Roanoke, Rockbridge, Rockingham, Shenandoah, Smyth, and Washington Counties (Figure 1; Ries and Somers, 1920). A few karst associated residual clays of white color and refractory character have been mined in Virginia (Figure 1). Clay was produced at the J.W. Goode property, Augusta County, by the Virginia Porcelain Company at the close of the Civil War, the Virginia Porcelain and Terra Cotta Company about 1873-1875, and the Virginia China Clay and Fire Brick Company still later (Ries and Somers, 1920). The Cold Springs Kaolin deposit, Augusta County, was worked from 1915 to 1951 for use as a filler in the manufacture of paper, paint, rubber, and linoleum (Ries and Somers, 1920; Dietrich, 1962). The Dickinson Fire Brick Company worked a kaolin deposit for the manufacture of fire brick in Rockbridge County (Ries and Somers, 1920).

FRESHWATER CARBONATE PRECIPITATES

Freshwater carbonate precipitates are found in two karst environments. Both of these types of deposits are depositional, but ironically they are precipitated from the same water that has formed the solutional features that define karst topography. The carbonate deposits which form along streams are referred to as travertine-marl, while the precipitates that form in caves also are travertine but those that were commercially extracted are herein termed cave onyx.

Travertine-marl deposits are known to occur along 60 streams in 18 counties of the Valley and Ridge province of Virginia. In their simplest form, these deposits consist of a downstream structural buildup of travertine with accumulations of marl forming a deltaic terrace upstream of the travertine. Deposits were utilized commercially in 12 (Figure 1) of the 18 counties between the mid 1800s and 1985 (Sweet and Hubbard, 1990). A total production of more than 1,570,000 short tons of Virginia travertine-marl is documented by Sweet and Hubbard (1990). One deposit in Alleghany County yielded a total of 387,760 short tons from 1914 to 1941. The principal use of this high calcium product was for agricultural lime. At a site in Montgomery County, travertine was burned to produce quicklime (Sweet and Hubbard, 1990). Travertine-marl had limited use as a flux in iron manufacturing (Hotchkiss, 1880; Ruffner, 1889).

Cave onyx was extracted in Botetourt, Rockbridge, and Rockingham Counties (Figure 1). Cave onyx was extracted in Botetourt, Rockbridge, and Rockingham Counties (Figure 1). Cave onyx was mined from Perry Saltpetre Cave, Botetourt County, in the 1920s (All, 1985, personal communication). Mineral resource records indicate that the Virginia Marble and Onyx Company, active in Botetourt County from 1918 to 1923, may have worked the Perry deposit, however, the market is not known. Mineral resource records indicated that terrazzo was produced in 1922 and 1923. The use of onyx for a terrazzo stone seems unlikely, however, it could explain the lack of scrap onyx typical of other sites. In Rockbridge County, Marble Cave, was mined for cave onyx. Mining was on a very small scale, but a graded roadbed leads to the cave entrance. Drill holes are found in two areas of the cave and pieces of a feather wedge and a well used conventional wedge were found in the cave. Accumulations of scrap onyx indicate that the onyx was probably worked to block dimensions. The onyx was cut by a gang saw at Rapps Mill according to local lore. The dates of mining and market for this onyx is unknown. The Onyx Hill deposit of Rockingham County was mined by the Virginia Minerals and Mining Company according to the present landowner (Paul Rohrer, 1988, personal communication). Deed searches did not turn up any information on this company, however, they did reveal that the Virginia Onyx Company paid for property and onyx rights at this site in 1893. Mining evidence includes two large onyx debris piles and a 2- to 12-foot wide by 60-foot long by 15-foot deep cut. Drill hole marks can be seen on some of the onyx debris. The destination of this onyx and its eventual form are not known. The Miller onyx deposit of Rockingham County was reportedly worked between 1870 and 1892 for tombstones (Hess, 1976). A second reference to this site mentions that J.E. Miller and Sons "...began making in 1892 tombstones of onyx found on their land. They used a circular rubbing bed operated by water power to polish the hard onyx" (May, 1976, p. 518). Several onyx gravestones have been located at J.E. Miller's church (Beaver Creek Church of the Brethren) in Rockingham County. The stones are dated from 1862 to 1872, but the date of the church building is 1868. Possibly the gravestones significantly postdate the burials and even the building of the church, or the graves were moved to the new church location after 1868. Two additional onyx gravestones, dated 1860(?) and 1870, are located in the Green Wood Cemetery, approximately two miles from the Miller deposit. Two pits, 25 feet by 50 feet by 6- to 8-feet deep and 35 feet by 60 feet by 10-feet deep, and two onyx debris piles are visible at the Miller site. In 1892 the Virginia Onyx Company was organized to mine and market onyx (Allen, 1893; May, 1976). The Miller site was the initial holding of this company. In addition to the Miller and Onyx Hill (Hinton) sites, onyx was reported from Garber's Church (May, 1976), but this site has not been located. The Virginia Onyx Company is known to have "shipped a large urn, two cones and a pyramid made of beautifully dressed onyx to New York in February, 1897" (May, 1976, p. 519).

EFFLORESCENT DEPOSITS

Efflorescent deposits are formed by the precipitation of minerals from pore water in rock or sediment. These minerals are soluble and usually accumulate only in locations where the sediment or rock and air contacts are sheltered. Although some of these minerals were utilized prehistorically (Watson, 1974), the only minerals of historical economic concern in Virginia are nitrates. The nitrate minerals of interest are nitrocalcite, nitromagnesite, and niter. The common name for niter is saltpeter, the archaic spelling of which has been used for the nitrate minerals mined from caves and refined for the making of black powder (gunpowder). Saltpetre was a very important commodity when imports were restricted during the American Revolution, the War of 1812, and the Civil War. Within the present boundaries of Virginia, which were different during each of the above conflicts, 76 saltpetre caves are known in the Valley and Ridge physiographic province (Figure 1; Hubbard, 1988; Hubbard and others, 1989). Saltpetre mining relicts include the remains of leaching vats, leachate and water collecting troughs, digging and scraping tools, boiling kettles, and evidence of mining such as leached petre dirt piles, digging marks, tally marks, and torch perches.

HYDROTHERMAL DEPOSITS IN KARST INDUCED POROSITY

The hydrothermal deposits in karst induced porosity are generally associated with paleokarst. The paleokarst topographic surface may have been destroyed or may be virtually unrecognized in the stratigraphic sequence and indicated only by an unconformity. Lead and zinc deposits occurring in the Ordovician-aged Knox and Beekmantown carbonate rocks have been identified as hydrothermal in origin and associated with paleokarst. An optical grade calcite deposit is included cautiously in this category, although further study is needed for a definitive genesis of this deposit.

Commercial deposits of zinc were deposited by mineral-forming solutions in the paleoaquifer associated with the Knox-Middle Ordovician unconformity, a former karst topography, at the top of the Mascot Dolomite in Tennessee and southern Virginia (Harris, 1971). The unconformity at the top of the laterally equivalent Beekmantown Formation of Ordovician age was the karst surface associated with the secondary permeability along which zinc and lead ores were deposited in the central and northern Valley and Ridge province.

Iceland spar, a variety of calcite, was mined for its optical properties in the vicinity of Timberville, Virginia during the 19th century (Figure 1). Located in the Ordovician-age Edinburg Formation, the deposit is of probable hydrothermal origin and may have been deposited along karst induced porosity. Spar deposition on a solutional surface of Edinburg limestone can be observed near the north end of the approximately 300 foot by 5 to 20 foot site. Isotope work needs to be done to determine the origin of the deposit.

FUTURE RESOURCE POTENTIAL

The potential for mineable manganese and clay, for refractory and whiteware uses, deposits associated with karst exists in Virginia. The more challenging and rewarding deposits will be associated with hydrothermal deposition associated with paleokarst. The identification of these sites is dependent on the recognition of both compositional signatures and paleosolutional features proximal to unconformities and faults capable of transmitting ore-bearing fluids. World-wide, other ore-grade deposits of possible hydrothermal and karst origin include copper, mercury, silver, uranium, and vanadium (Quinlan, 1972).

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INDUSTRIAL SILICA RESOURCES IN VIRGINIA

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INTRODUCTION

Quartz and quartzite were utilized as tools and weapons by the earliest inhabitants of Virginia, roughly 11,000 years ago (McCary, 1986). To the Indians, the value of these rocks was in the workability, hardness, and their ability to hold a sharp edge. Not all quartz or quartzite could be used, however, the stone would need to meet certain requirements to produce useful implements. Impurities, weathering, or fractures within the rock would prevent proper shaping, adequate strength, or the ability to hold an edge. The search for such a stone was not easily accomplished, as is indicated by the large number of discarded blanks found at Indian quarry sites. Thus did our early predecessors in the mineral industry discover the now age-old intrinsic problem of quality control.

To this end, our industrial silica industry has not changed. In twentieth-century Virginia, silica has been used for glass manufacture, foundry sand, traction sand, filtering, metallurgical flux, conversion to cristobalite, oscillator-grade crystal, coal-washing, production of ferrosilicon, cleansers, sandblasting, stone sawing, and silica flour as a component in fiberglass. Each of these uses of silica has specific chemical and physical parameters that must be met to produce an acceptable product. In general, the quartz must meet maximum silica content requirements while containing minimum amounts of contaminants. Major detrimental elements include alumina, iron, titanium, and calcium and magnesium oxides. Also detracting from some end-use products are elements such as arsenic, chromium, cobalt, and phosphorous.

In 1989, Virginia silica companies produced glass sand, filter sand, traction sand and cristobalite. Though the bulk of these products were produced primarily in the Valley and Ridge province, some were also produced in the Piedmont, Blue Ridge, Appalachian Plateaus, and Coastal Plain provinces (Figure 1). The following discussion lists the various silica-producing formations in Virginia by physiographic province. Because the Coastal Plain province is limited to production of traction sand, and filter sand, it will not be discussed in this paper.

VALLEY AND RIDGE PROVINCE

ANTIETAM-ERWIN FORMATION

The lower Cambrian-aged Antietam or Erwin Formation (hereafter called Antietam Formation) crops out and forms prominent ridges on the west flank of the Blue Ridge Mountains. It is overlain by the Shady Dolomite and underlain by

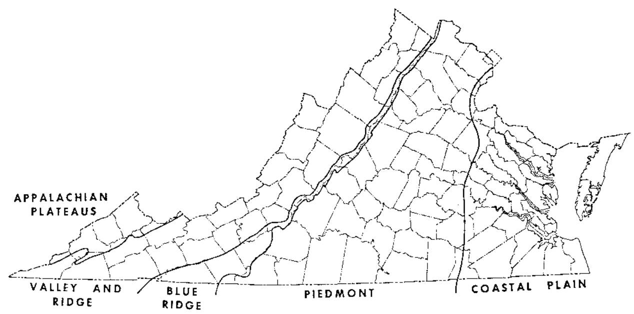

Figure 1. Physiographic provinces of Virginia.

the Hampton or Harpers Formation. The Antietam Formation varies in thickness, but is at least 1500 feet thick in the central Shenandoah Valley (Butts, 1940). This formation can be divided into upper and lower units: the lower unit is characterized by clean, massive, well-indurated quartzite. The quartzite has interlocking quartz grains and minor impurities of tourmaline, epidote, microcline and plagioclase feldspar. The upper part of the Antietam Formation is cemented with carbonate which upon weathering produces a surface which is pitted and friable. The upper unit also has thin beds and commonly contains abundant amounts of iron as coatings on the quartz grains.

The Antietam quartzite has been quarried for ballast and ferrosilicon productions east of Waynesboro, Augusta County, and also in Arnold Valley, Rockbridge County (Figure 2). Samples of the lower unit of the Antietam Formation collected by Sweet and Wilkes (1986), produced a material too well cemented for sieve analyses, but an average of two beneficiated chemical analyses indicates a potential use as metallurgical material:

Constituent	Percent
SiO_2	97.54
Al_2O_3	.29
Fe_2O_3	.02
MgO	.02
CaO	.00

An average of two beneficiated chemical analyses reported by Sweet (1981) from Augusta and Rockbridge Counties indicates this part of the Antietam has potential use as glass-grade sand:

Constituent	Percent
SiO_2	99.30
Al_2O_3	.43
Fe_2O_3	.25
MgO	.02
CaO	.01

Figure 2. Quartzite, Antietam Formation, at the Greenlee quarry, Natural Bridge, Rockbridge County.

High-silica sand has also been produced from weathered Antietam-Erwin Formation sandstone and quartzite at Lots Gap and two other localities in Wythe County.

TUSCARORA-CLINCH FORMATION

The lower Silurian-age Tuscarora Formation, also known as the Clinch sandstone in the southern Valley and Ridge province, is a very fine- to very coarse-grained sandstone/quartzite which locally contains quartz pebbles. The rock is typically well indurated but at some localities is poorly cemented and weathers to loose sand. This unit varies in thickness (up to 200 feet thick) and degree of consolidation throughout its outcrop area. Because of its resistance to weathering, it is most commonly recognized as the major ledge or ridge former (Figure 3).

Beneficiated chemical analyses by Sweet (1981), Sweet and Wilkes (1986), and Lovett (1988) indicate the Tuscarora has potential use as a high-silica product:

Constituent	No. Valley(%)	Cent. Valley(%)	So. Valley(%)
SiO_2	99.04	98.97	98.00
Al_2O_3	.32	.56	.78
Fe_2O_3	.17	.36	.25
MgO	.02	.02	<.01
CaO	.05	.00	<.03

KEEFER SANDSTONE

The upper Silurian age Keefer Sandstone is typically a white to brown, very fine- to medium-grained, resistant quartzite to variably friable sandstone. Quartz-pebble conglomerate beds, less than five feet thick, occur locally. Quartz grains are bonded by quartz overgrowths. The Keefer is overlain by the Wills Creek Formation, a limestone sequence, and underlain by the Rose Hill Formation, a distinctive red sandstone and shale sequence. Beneficiated chemical analyses by Sweet (1981) and Sweet and Wilkes (1986) indicates the Keefer has potential as high-silica sand:

Constituent	No. Valley(%)	Cent. Valley(%)
SiO_2	99.33	98.63
Al_2O_3	.33	.64
Fe_2O_3	.23	.07
MgO	.01	.03
CaO	.02	.00

Figure 3. Tuscarora Formation, which forms many ridge tops in the central Valley and Ridge province, Back Creek Mountain, Bath County.

RIDGELEY-ORISKANY SANDSTONE

The lower-to-middle Devonian Ridgeley or Oriskany sandstone (hereafter called the Ridgeley sandstone) is found within the Valley and Ridge province and has been proven to be a viable silica sand. The Ridgeley is typically a fossiliferous white to light-gray sandstone with calcareous cement. Jointing and fracturing of the unit by dominantly compressional forces has allowed ground water to enter the unit and leach the cementing material. This produces a loosely consolidated sandstone in outcrop. The Ridgeley is bounded above by the Needmore shale or Huntersville chert which is underlain by the lower Devonian carbonate sequence (Helderburg group). The thickness of the Ridgeley varies from more than 300 feet in the northern Valley and Ridge, to less than 10 feet in the south-central Valley and Ridge. In the southern Valley, the Ridgeley, Healing Springs, and Clifton Forge sandstones coalesce to form the Rocky Gap Sandstone, and in the extreme southwestern Valley, the Wildcat Valley Sandstone. Unimin Corporation in Frederick County is presently quarrying the Ridgeley for use as glass sand. Castle Sands Company in Craig County is currently producing from the Ridgeley for masonry sand and concrete aggregate.

Beneficiated chemical analyses by Sweet (1981) and Sweet and Wilkes (1986) indicate a good potential for the Ridgeley to be utilized as high-silica sand:

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Constituent	No. Valley(%)	Cent. Valley(%)
SiO_2	99.30	98.37
Al_2O_3	.15	.78
Fe_2O_3	.13	.13
MgO	.01	.05
CaO	.19	.00

HINTON FORMATION

The upper Mississippian-age Hinton Formation is found in the southwestern Valley and Ridge and can be divided into four rock units based on lithologic differences. Two units, the Tallery Sandstone Member and the Stony Gap Sandstone Member were examined by Lovett (1988) and found suitable for high-silica resources.

The Tallery Sandstone Member is the uppermost unit of the Hinton Formation and is 55 to 125 feet thick. It is friable to well indurated, fine- to coarse-grained, thin to massive bedded, and locally conglomeratic. Three samples by Lovett (1988) produced the following unbeneficiated average analyses:

Constituent	Percent
SiO^2	98.00
Al_2O_3	2.00
Fe_2O_3	.54
MgO	.03
CaO	.03

Initial testing indicates the Talley Sandstone Member has a potential for glass-grade and metallurgical sand.

The Stony Gap Sandstone is the lower unit of the Hinton Formation and is 160 to 420 feet thick. It is friable to well indurated, very fine- to medium-grained, and thin to thick bedded. Five samples collected by Lovett (1988) indicate this unit has potential as a high-silica product:

Constituent	Percent
SiO^2	97.20
Al_2O_3	2.10
Fe_2O_3	.97
MgO	.08
CaO	.38

APPALACHIAN PLATEAUS PROVINCE

LEE FORMATION

The lower Pennsylvanian-age Lee Formation, which crops out along Pine Mountain in Wise and Dickenson Counties, contains alternating thick beds of quartzarenite and interbedded siltstone and shale. In this area, the formation can be described as consisting of an uppermost quartzarenite (Bee Rock Sandstone Member, Figure 4), an intervening shale unit (Hensley Shale Member), and a lower quartzarenite (Middlesboro Member).

The Middlesboro Member of the Lee Formation consists of an upper and lower quartzarenite. The upper quartzarenite is 100 to 200+ feet thick and is generally very light gray to yellowish-gray, fine- to coarse-grained, thin to massive bedded, and conglomeratic near its base. It has been quarried on Pine Mountain at the head of Blue Head Branch, south of Elkhorn City. The quarried rock consists of a lower conglomeratic unit which grades upward into a white, fine- to medium-grained sandstone. The conglomerate contains rounded quartz pebbles up to one inch in diameter, which accentuates bedding in outcrop. The Silica Corporation of America produced glass and coal-washing sand from this quarry from 1960 to 1962. Test data (McGrain and Crawford, 1959, and Hollenbeck and others, 1967) of the upper sandstone unit indicated of 99.30% SiO_2, 0.07% Fe_2O_3, and 0.33% Al_2O_3. Lovett (1988) shows unbeneficiated samples with average analyses of 98% SiO_2, 0.22% Fe_2O_3, and 1.8% Al_2O_3. The lower conglomeratic unit contained 99.3% Sio_2, 0.05% Fe_2O_3, and 0.08% Al_2O_3 (McGrain and Crawford, 1959, and Hollenbeck and others, 1967). Trace amounts of zircon, tourmaline, rutile, kyanite, and opaque material were also found throughout the unit. Fluorite was found in small concentrations in the conglomeratic unit. Screen analyses indicate that most of the iron, alumina, and titanium minerals in the two units are concentrated in the minus 140-mesh range.

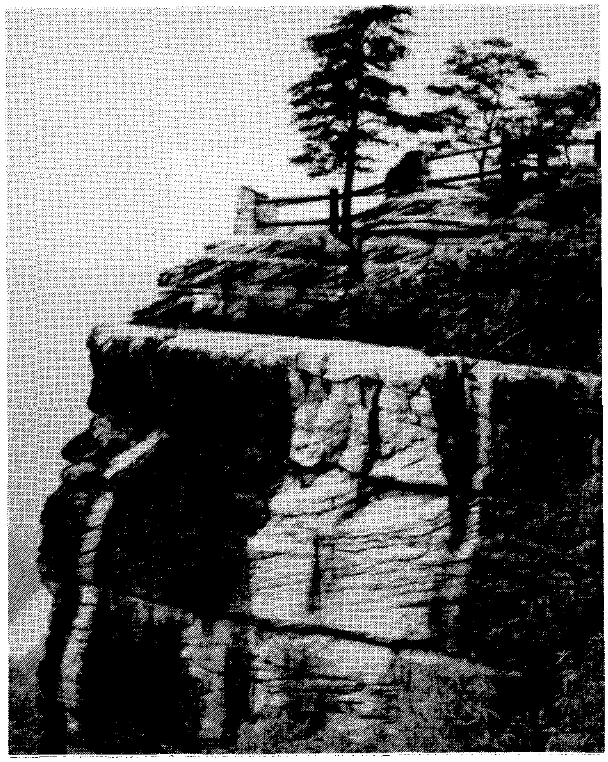

Figure 4. Bee Rock sandstone member of the Lee Formation, Breaks Interstate Park, Virginia-Kentucky. Photograph by T.M. Gathright, II.

The lower quartzarenite of the Middlesboro Member of the Lee Formation is 150 to 250 feet thick, very light gray to very pale orange, fine- to coarse-grained, locally conglomeratic, thin to massive bedded and can be locally interbedded with shale, siltstone, and coal. It was quarried for coal washing sand north of Pound on the east flank of Pine Moun-

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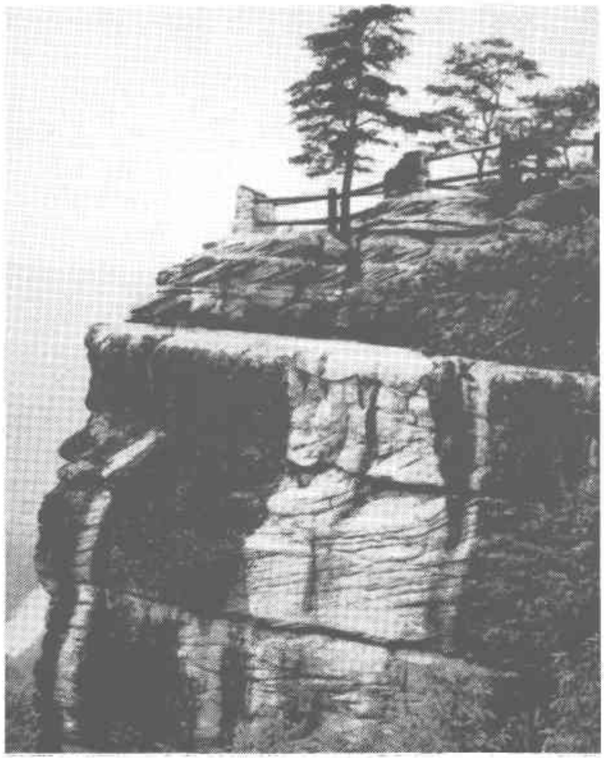

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BLUE RIDGE AND PIEDMONT PROVINCES

QUARTZ VEINS

Raw quartz, known as "bull quartz", is commonly found in the Blue Ridge and Piedmont provinces. It occurs most commonly as injected veins, but also occurs in the core of some pegmatite bodies. Both occurrences have been mined in Virginia for silica.

The intrusion of vein quartz occurred as a late event in Virginia's geologic history. The composition of these veins mirror the chemical composition of the originating magma body, and to a lesser extent the composition of the host rock. Because the silicate group comprises a significant portion of deep seated magma, quartz is abundantly represented in vein deposits. In Virginia, minerals that are associated with quartz veins and that have been commercially produced include gold and silver. Locally, however, a nearly pure (greater than 90% SiO_2) quartz was formed. Several quartz vein deposits of high purity and in excess of 2.5 million tons have been noted in Virginia and may be suitable for metallurgical grade material.

A quartz vein located south of Meadows of Dan, Patrick County was quarried in 1964 to extract metallurgical quartz to be utilized in Pittsburgh, Pennsylvania as a flux (Figure 5). The vein is exposed for 400 feet, has a width of 75 feet and soil covers the vein for an additional 900 feet. Analyses show this material to consist of 99.10% SiO_2, 0.57% Al_2O_3, and no detectable of Fe_2O_3 (Sweet, 1986).

Figure 5. Quartz vein, Meadows of Dan, Patrick County, utilized in mid-1960s as metallurgical flux.

A quartz vein on the Otter River in Campbell County has a potential resource of more than 2.6 million short tons of high-silica quartz.

Another vein in Fluvanna County, mined by Palmyra Stone Company in 1964, has an estimated one million ton reserve. Analyses of the Palmyra Stone Company vein show results of 99.05% SiO_2, 0.66% Al_2O_3, and no Fe_2O_3 (Sweet, 1986).

West of Carters Bridge in Albemarle County, a quartz vein can be traced for over 1700 feet with a measurable width of about 70 feet. The quartz in this vein appears to be unusually pure.

Quartz commonly occurs in the core of pegmatites and may be pure enough to constitute a high-silica resource. Locations that may have a potential for silica extraction are the Champion, Jefferson No. 3, and Pinchbeck No. 1 mines in Amelia County, and the Wheatly mine in Bedford County.

CONCLUSIONS

Currently in Virginia, silica is produced for glass manufacture, filter sands, traction sand, and conversion to cristobalite. Potential for silica resources for these and many other uses have been identified in all of the phiyographic provinces of the state. Each province has unique characteristics in regard to the type of silica material available, extraction history, transportation, and future developmental potential. Studies by the Virginia Division of Mineral Resources have addressed silica resources in the state and invite inquiries as to their development potential.

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tain. The quarry was last worked by Southwest Sand Company, Inc. in 1974. Former operators were C.E. Robertson, and Skyline Sand Company, Inc. in the early 1960s. Chemical analyses indicate 97.0 to 99.2% SiO_2. Lovett (1988) described this unit is suitable for metallurgical material.

BLUE RIDGE AND PIEDMONT PROVINCES

QUARTZ VEINS

Raw quartz, known as "bull quartz", is commonly found in the Blue Ridge and Piedmont provinces. It occurs most commonly as injected veins, but also occurs in the core of some pegmatite bodies. Both occurrences have been mined in Virginia for silica.

The intrusion of vein quartz occurred as a late event in Virginia's geologic history. The composition of these veins mirror the chemical composition of the originating magma body, and to a lesser extent the composition of the host rock. Because the silicate group comprises a significant portion of deep seated magma, quartz is abundantly represented in vein deposits. In Virginia, minerals that are associated with quartz veins and that have been commercially produced include gold and silver. Locally, however, a nearly pure (greater than 90% SiO_2) quartz was formed. Several quartz vein deposits of high purity and in excess of 2.5 million tons have been noted in Virginia and may be suitable for metallurgical grade material.

A quartz vein located south of Meadows of Dan, Patrick County was quarried in 1964 to extract metallurgical quartz to be utilized in Pittsburgh, Pennsylvania as a flux (Figure 5). The vein is exposed for 400 feet, has a width of 75 feet and soil covers the vein for an additional 900 feet. Analyses show this material to consist of 99.10% SiO_2, 0.57% Al_2O_3, and no detectable of Fe_2O_3 (Sweet, 1986).

Figure 5. Quartz vein, Meadows of Dan, Patrick County, utilized in mid-1960s as metallurgical flux.

A quartz vein on the Otter River in Campbell County has a potential resource of more than 2.6 million short tons of high-silica quartz.

Another vein in Fluvanna County, mined by Palmyra Stone Company in 1964, has an estimated one million ton reserve. Analyses of the Palmyra Stone Company vein show results of 99.05% SiO_2, 0.66% Al_2O_3, and no Fe_2O_3 (Sweet, 1986).

West of Carters Bridge in Albemarle County, a quartz vein can be traced for over 1700 feet with a measurable width of about 70 feet. The quartz in this vein appears to be unusually pure.

Quartz commonly occurs in the core of pegmatites and may be pure enough to constitute a high-silica resource. Locations that may have a potential for silica extraction are the Champion, Jefferson No. 3, and Pinchbeck No. 1 mines in Amelia County, and the Wheatly mine in Bedford County.

CONCLUSIONS

Currently in Virginia, silica is produced for glass manufacture, filter sands, traction sand, and conversion to cristobalite. Potential for silica resources for these and many other uses have been identified in all of the phyiographic provinces of the state. Each province has unique characteristics in regard to the type of silica material available, extraction history, transportation, and future developmental potential. Studies by the Virginia Division of Mineral Resources have addressed silica resources in the state and invite inquiries as to their development potential.

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BRUCITE MARBLE OCCURRENCES ALONG ORDOVICIAN BEEKMANTOWN DOLOMITE AND EOCENE BASALT AND ANDESITE DIKE CONTACTS, HIGHLAND COUNTY, VIRGINIA

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ABSTRACT

Naturally occurring brucite, $Mg(OH)_2$, is currently produced in the United States from only two deposits in Texas and Arizona. Brucite is marketed as a detoxification agent in textile manufacture, for use with PVC plastics, as a TiO_2-extender in paints, and as a fire retardant.

Brucite was first noted in Virginia by Giannini in 1987 at an abandoned dolomite quarry used for crushed stone near Hightown, Highland County, in the Valley and Ridge Province of westernmost central Virginia. The host rock is dolomite of the Lower Ordovician Beekmantown Formation. Further investigation was made with three 60 foot drill holes. Two predazzite marble zones (12- 24% brucite + calcite) of 15 feet and 26 feet were encountered along a kinked contact in a steeply dipping, 25-30 foot wide porphyritic biotite plagioclase felsic andesite of Eocene age. The brucite marble alteration zone outcrops for 36 feet at the top of the quarry and continues at shallow depths in the form of a "Christmas tree" that is apparently joint-controlled. The brucite-calcite/andesite contact shows brecciation and small amounts of hydrated alteration minerals including monticellite ($CaMgSiO_4$), analcite ($NaAl_2O_6.H_2O$), natrolite ($Na_2Al_2Si_3O_{10}$), artinite ($Mg_2CO_3(OH)_2.3H_2O$), hydromagnesite ($Mg_5(CO_3)_4.4H_2O$, chabazite ($CaAl_2SiO_4.6H_2O$, and serpentine group minerals. The smaller andesite dikes and much of the larger andesite dike has no apparent surface alteration. All dikes and the enclosing dolomite have a northeast strike. A small 3 foot diatreme breccia containing well-rounded pebbly and sharply angular clasts of hematitic quartzite, chert, and dolomite in a mafic igneous matrix also outcrops in the quarry.

The Hightown brucite occurrence is located on the western, overturned limb of the Hightown anticline, just east of the Allegheny Front. Ten other dikes of basalt, andesite, and trachyte in contact with the dolomite were also examined within the doubly plunging structure and two additional brucite occurrences were noted: 1.5 mile north-northeast and 1.75 mile northeast of Hightown quarry.

The brucite occurrences have been generated in a tectonic setting of Jurassic to Eocene dike swarms related to a major Appalachian hotspot that may represent the reactivated intersection of two rift-related fracture systems in basement rocks.

INTRODUCTION

Brucite is produced in the United States at two deposits, the largest in west Texas at Marble Canyon, and another recently discovered deposit in Arizona. The sole producer at present is RMcMinerals, who sell -325 mesh, >15% brucite from Marble Canyon, at $0.25 a pound ($500/short ton) and high grade (>90% brucite) at $0.40/pound from the Arizona deposit. Brucite is marketed as "Magnum-White" as a replacement for TiO_2 in high quality paints, as a fire retardant, and for use with PVC plastics. Brucite may also have some potential in ink manufacture (McCreless, 1990). The chief market for brucite comes from the textile industry in which it is used as a detoxifying agent for hazardous dye components such as antimony and bromine. R. McMinerals sells Texas brucite to a textile plant in Georgia for this purpose (McCreless, personal communication, 1989).

Brucite was first identified in Virginia by Giannini and others (1987) from loose shales fallen from near the top of the highwall of an abandoned crushed stone quarry, located on the east side of State Road 640, 2.3 miles by road northeast of U.S. Highway 250 at Hightown (Figure 1). The property is owned by N. Dudley and Agnes Rexrode, Mount Solon, Virginia.

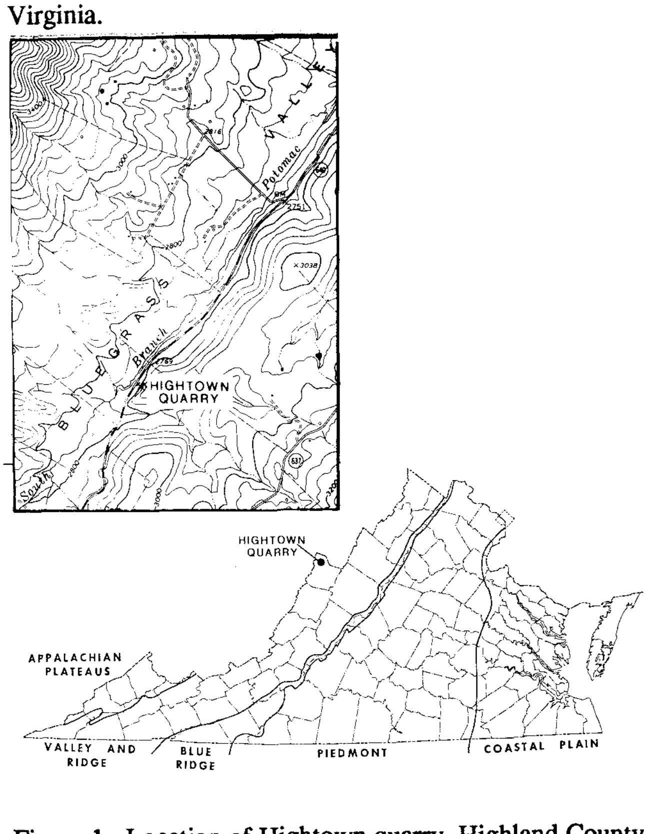

Figure 1. Location of Hightown quarry, Highland County, Virginia.

The original samples were dislodged blocks up to two feet across with dark gray to black weathered surfaces. Apparently fresh white surfaces had pale bluish-white, greenish-white, yellowish, and purplish-white zones. The brucite-calcite marble contained minor serpentine minerals and was estimated to be 17% brucite and 83% calcite on average (Giannini and others, 1987). The brucite-bearing slabs were directly below a five foot thick altered zone about 30 feet long at a contact between and intruding Eocene andesite dike and the enclosing dolomite of the Lower Ordovician Beekmantown Formation.

In following up the initial discovery, a 36 x 20 foot white brucite outcrop was discovered on top of the rim of the quarry. The brucite-calcite marble is brecciated, fractured and intruded with narrow 1 cm gray andesite veins filling the fractures. A total of 180 feet was funded to drill three holes on the Hightown occurrence, and this report is a summary of the preliminary reconnaissance findings.

The writer also investigated ten other dikes within the Beekmantown Formation within the Hightown anticline and noted two other brucite-bearing contacts outside the quarry area (Figure 2). As part of the preliminary reconnaissance the writer also briefly investigated an Eocene basalt intrusive at Mole Hill, about 3 miles west of Harrisonburg, Rockingham County, and 32 miles east of Hightown quarry (Figure 3). The Mole Hill basalt is a larger intrusive plug at surface, 1200 x 2000 feet, than all of the other dikes and intrudes dolomite. However the contact is completely concealed.

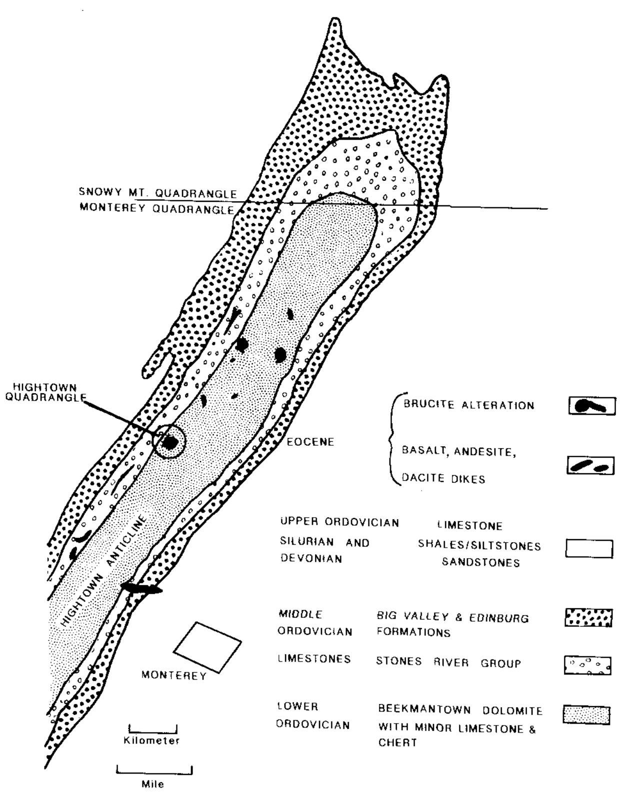

Figure 2. Generalized geology of area around Hightown quarry in northern portion of Hightown anticline. After Parrott (1948).

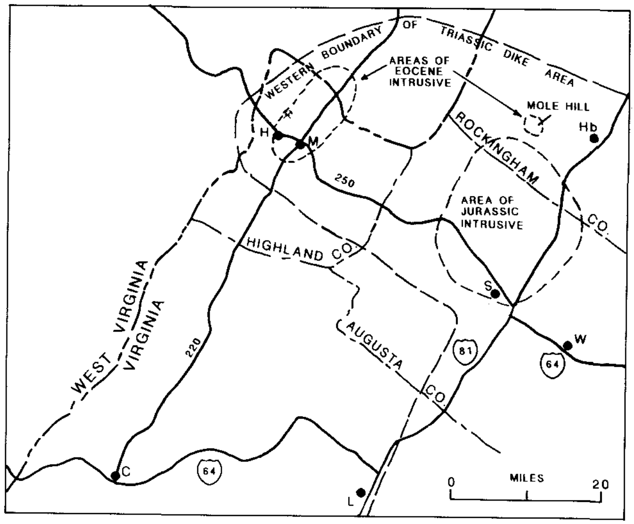

Figure 3. Mole Hill basalt and areas of Eocene and Jurassic dike swarms and volcanic plugs, central-western Virginia.

GEOLOGY

The Hightown quarry is located in the Blue Grass Valley of Highland County which lies within the Valley and Ridge province of Virginia (Figure 1). The quarry is entirely within the Lower Ordovician Beekmantown Formation which consists largely of dolomite with minor limestones and thin chert beds and lies on the western overturned limb of a doubly plunging Hightown anticline mapped by Parrott (1948). This fold is at the western border of the Valley and Ridge province. Valley and Ridge rocks consist of lower and middle Paleozoic unmetamorphosed shales, siltstones, sandstones, limestones, dolomites, and minor cherts with high amplitude, plunging folds imbricately thrust to the northwest. Major northeast-southeast trending ridges are supported by Silurian quartz arenites of the Tuscarora and equivalent formations. Valleys are underlain by siltstone, shale, and carbonate rocks. Much of the Valley and Ridge is allocthonous with detached and repeated structures.

Blue Grass Valley is underlain by Lower Ordovician Beekmantown and Middle Ordovician limestones of the "Stones River" (Murfreesboro, Mosheim and Lenoir limestones) and "Lowville" (Big Valley and Edinburg) formations. The Beekmantown Formation is mostly dolomite with thin limestone beds, and thin 2-foot, fossiliferous chert beds (Parrott, 1948). The flanking ridges to the valley, Lantz Mountain on the northwest and Monterey Mountain on the southeast, are supported by, tough, resistant quartz arenite of the Silurian Tuscarora Formation, underlain by the Upper Ordovician Juniata Formation with red and brown sandstones and shales. Underlying the Juniata and outcropping on the lower slopes of both sides of the Blue Grass Valley is the Ordovician Martinsburg Formation which is composed of shale and shaly limestone in the lower part and shale and sandstone near the top. The Martinsburg is equivalent to the Upper Ordovician Reedsville shale and the Ordovician and Trenton limestone.

Although both the Appalachian Plateaus and Valley and Ridge provinces are locally intruded by Mesozoic and Tertiary dike swarms, there are no large intrusives on surface of several or tens of miles diameter with metamorphic aureoles and no regional metamorphism in marked contrast to the pervasive metamorphism, plutonism, and volcanicity of the Blue Ridge and Piedmont provinces to the east of the Valley and Ridge. During the Paleozoic, Valley and Ridge rocks have recorded hydrothermal activity from metal-rich and silica-saturated saline brines containing iron, manganese, lead, zinc, and barite, particularly the Cambrian (Erwin, Shady, Rome, and Copper Ridge Formations, and Ordovician (Beekmantown Formation). Thin Ordovician and Devonian tuffs, now bentonitic clays, are the only other surface evidence of nearby igneous activity in the Valley and Ridge during Paleozoic time.

Small igneous dikes and volcanic plugs of the Valley and Ridge have long been recognized, with the first detailed descriptions by Rogers (1884), Darton and Diller (1890), Darton and Keith (1898), Darton (1899), and Watson and Cline (1913). These early workers recognized a basalt porphyry and a fine grained porphyritic felsite or granite felsophyre. The basalt was considered by Watson and Cline (1913) to be Triassic diabase dikes. Dennis (1934) continued further investigations on dike rocks of the Shenandoah Valley.

The geologic mapping framework for modern field investigations was provided by Butts (1940, 1941). A regional study of the Ordovician limestones was made by Kay (1956). Restricted mapping of individual anticlinal structures in western Highland County was done by Clough (1948), Parrott (1948), Tarleton (1948), and Ramsay (1950). Parrott (1948) in mapping the northern part of the Hightown anticline, the structure which underlies and surrounds the Hightown quarry, recognized felsophyre, trachyte, and basalt and noticed sedimentary clasts in some of the dike rocks. Garner (1956) studied the dike swarms in adjacent Pendleton County, West Virginia and Johnson and Milton (1963) described teschenite, picrite, and nepheline syenite dikes in Augusta and Rockingham counties reporting a Jurassic age (152 m.y.) for some of them. Rader and Griffin (1960) suggested that the dikes at Hightown quarry previously called granite felsophyre, should be called andesite porphyry. Fullager and Bottino (1969) assigned an Eocene age, 47 m.y., to the Hightown quarry dikes and called them andesite porphyry. Kettren (1970) examined the petrology and relationship to structure and host rock of 60 intrusives within a nine square mile area northeast of Monterey and was followed by Hall (1975) who examined the chemistry and mineralogy of 80 dikes within Highland County. Hall noted that the dike petrology ranged from basalt to andesite with some trachytes and rhyolites and that the dikes cut formations from the Ordovician Beekmantown Formation to the Marcellus shale with thicknesses from 1 to 150 meters and lengths up to one kilometer. The paleomagnetic pole directions for several felsite (andesite) intrusions in Highland County were determined by Loevlie and Opdyke (1974) who found that the pole direction agrees with early Tertiary poles from the western United States and with the Eocene radiometric ages of Fullagar and Bottino (1969). Rader and others (1986) summarized descriptions of the Hightown quarry and nearby Trimble Knob, southwest of the town of Monterey.

Large scale alteration in the country rock in areas of dike swarms has not been previously documented. Alteration in haloes around xenoliths was noted in small aureoles generally less than 1 cm thick (Mitchell and Freeland, 1986). A highly altered basaltic-andesitic dike 2 miles south-southwest of Hightown quarry (Figures 3 and 4) contains limestone xenoliths up to six cm across with haloes of melilite group minerals, magnetite, and perovskite. Later alteration of the dike converted the basalt to an analcite-rich rock with aragonite, calcite, phillipsite, thomsenite, and pyrite on crosscutting fractures and the xenoliths to tobermorite, ettringite, aragonite, thaumasite, hercynite, and coarser calcite (Mitchell and Freeland, 1986). Another example of very restricted, internal alteration occurs in eastern Highland County in an Eocene sill intruding Upper Silurian limestone with the formation of the very rare tacharanite, $Ca_{12}Al_2Si_{18}O_{51}.18H_2O$, as an amygdule filling (Mitchell and Giannini, 1987).

Figure 4. Roadside outcrop of altered columnar basalt along State Road 637, 2 miles south-southwest of Hightown quarry.

Southworth and Gray (1988) examined the major element and trace element chemistry of 46 dikes in Pendleton and Highland Counties and concluded that the chemistry and petrology of the dikes suggest a mantle or lower crustal source of rift related origin, possibly from extensional reactivation near the intersection of two basement fracture zones. Geophysical evidence that might support a rift interpretation for location of the dike swarms is shown in the simple Bouguer anomaly that straddles the West Virginia-Virginia state line along the Allegheny structural front (Figure 5). The gravity anomaly is from -60 to more than -80 milligals and could reflect a basement topographic low, perhaps related to a buried reactivated rift system. Terrain corrections would not affect the shape of this broad anomaly and an extreme case would not amount to more than 5-7 milligals (S.S. Johnson, personal communication, 1990). Rifts systems are widely considered to be driven by mantle plume convection cells. This is one explanation that might account for the dike swarm emplacement.

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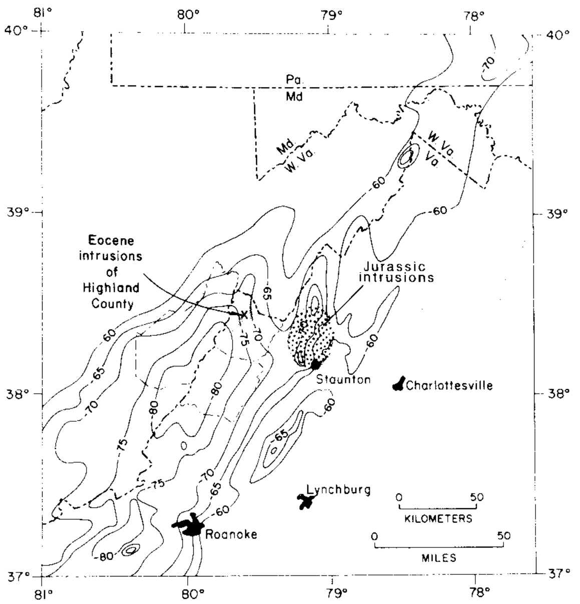


Figure 5. Eocene and Jurassic intrusions of west central Virginia in relation to simple Bouguer gravity values.

RESULTS OF INVESTIGATION

The Beekmantown Formation at the Hightown quarry dips at about 75 degrees to the southeast and is overturned to the northwest. It is a bluish gray, thick bedded fine to medium grained dolomite with minor thin limestone beds. At the upper highwall the dolomite is light gray (Figure 6). Some exposures at the quarry are finely laminated and contain algal mat mudcracks indicating a peritidal shoreline environment (Figure 7). In plain view there are three felsic biotite andesite dikes trending northeast cutting the dolomite beds (Figure 8). A view of the quarry highwall showing exposures of the dikes near and at the top is shown in Figure 9. Note the top of the drill rig in the extreme top right corner showing the location of drill holes #1 and #2. The two dikes exposed in the quarry face are 3 to 5 feet wide and contain carbonate xenoliths at their contacts. The andesite dike at the top of the high wall is about 25-30 feet thick near the center of the quarry and dips steeply to the southeast as does the dolomite which it cuts. The andesite dike on the top of the quarry is gray to medium gray with light gray in fresh core. It weathers to a brown, punky rock with biotite visible as hydrobiotite flakes in the soil. The upper dike is porphyritic, with biotite, pyroxene, and plagioclase phenochrysts. The plagioclase phenochrysts are 1-2 mm wide laths 2-12 mm long and 10-15 mm rhombs, some of which might be sanidine. In thin section the plagioclase is zoned and ranges from oligoclase to labradorite in composition. Some grains show Carlsbad twinning. The groundmass is microcrystalline plagioclase, hornblende, and contains accessory magnetite, pyrite, and apatite. The dike contact with the Beekmantown dolomite on a slope back from the quarry face on the southern end of the quarry shows no

Figure 6. View to northeast from top of Hightown quarry of exposures of Beekmantown dolomite.

Figure 7. Algal mudcracks on surface of steeply dipping, overturned beds of Beekmantown dolomite. View is to southeast and scale is indicated by hardhat.

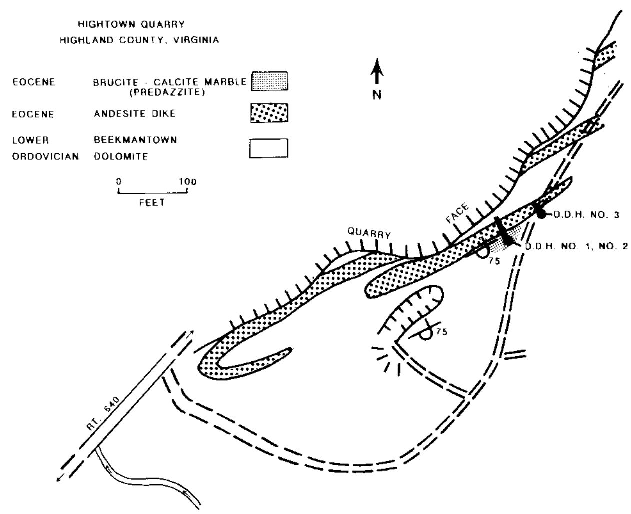
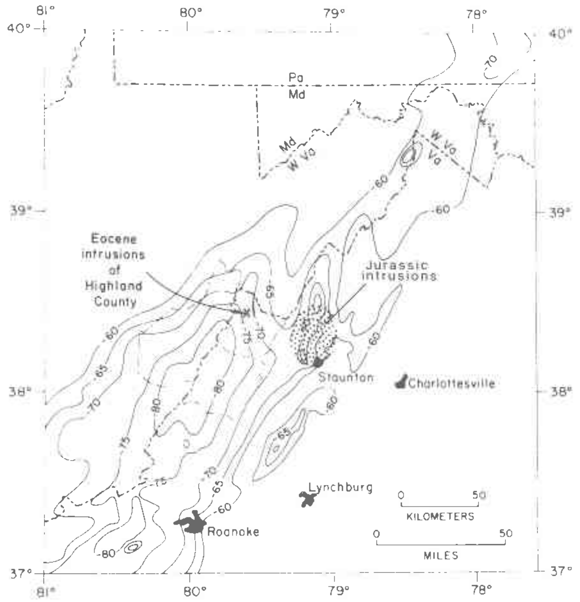


Figure 8. Geologic map, plain view, Hightown quarry.



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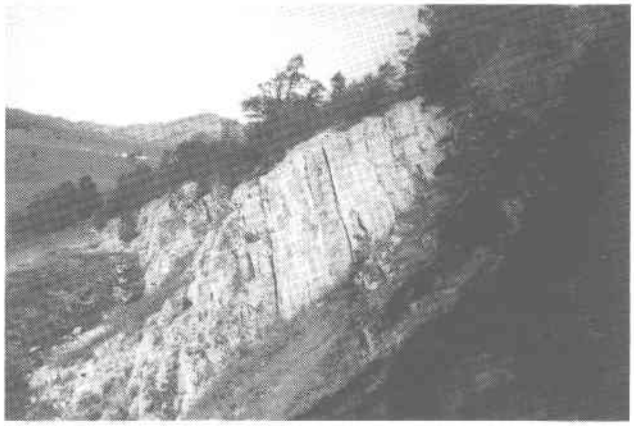

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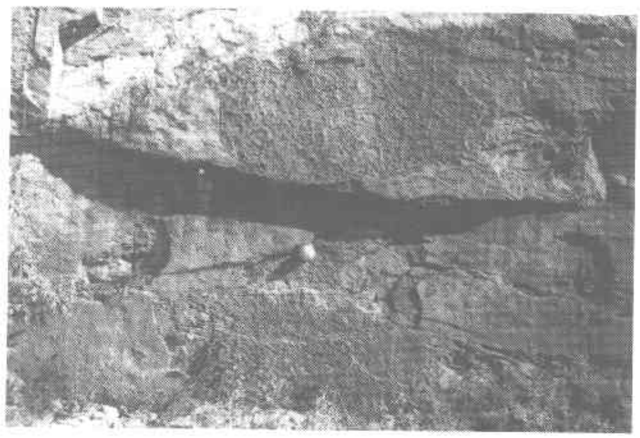


Figure 7. Algal mudcracks on surface of steeply dipping, overturned beds of Beekmantown dolomite. View is to southeast and scale is indicated by hardhat.

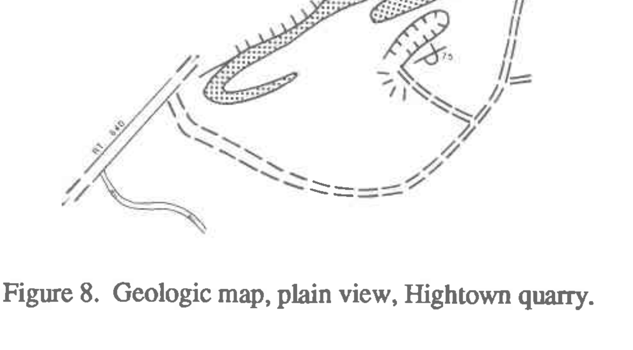


Figure 8. Geologic map, plain view, Hightown quarry.

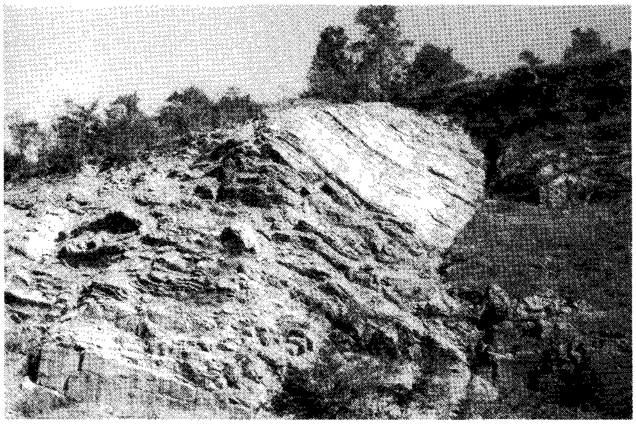


Figure 9. View to southeast of middle portion of Hightown quarry. Top of drill rig on site of holes 1 and 2 can be seen in extreme upper right.

Figure 10. Andesite dike and Beekmantown dolomite contact showing no apparent alteration, southern end of Hightown quarry.

apparent alteration (Figure 10).

Additionally there is a small diatreme breccia pipe containing both rounded, pebble-like, and angular clasts, and a younger, greenish-gray, northwest-trending basalt dike cutting one of the andesite dikes. The pebbles are assumed to be derived from the wall rock by gas-fluidization and corrosion as Johnson and others (1971) have previously suggested. All three of the main andesite dikes are subparallel and trend northeast.

About midpoint on top of the quarry an area of about 36 by 20 feet of outcrop of brecciated white brucite-calcite rocks with gray andesite vein-fillings occurs (Figure 11). Drilling was done on the outcrop shown in Figure 12 with a vertical hole and a second hole from the same site on the brucite-calcite rock outcrop but at 60 degrees to the northwest. Figure 12 depicts the drill hole locations in three dimensions. In the vertical hole (D.D.H. #1) two brucite-calcite zones were encountered with thicknesses of 15 and 26 feet. Core was examined by X-ray diffraction every foot and significant (10-25%) brucite and calcite was found in nearly continuous sequence. Three drill core samples in which brucite was lacking may represent thin limestone beds within the dolomite. Some dolomite was found in addition to brucite and calcite near the ends of the brucite sections. Estimation by comparing area under X-ray peak height was used to estimate values of 12-24% by volume. In brucite-bearing zones the brucite was seen in thin section as small, disseminated, 1-2 mm granules and in fracture filling in brecciated rock. Based on the data from hole #2 at 60 degrees, which did not intersect the zone from which the slabs fell, the writer has interpreted the drill data as dedolomitization along a joint system in a kind of "Christmas tree" pattern, and not a fault. It may be speculated that there could well be more kinked, altered joints with brucite at depth, and that this point is a volcanic hot spring pipe near the surface. The evidence of brecciation, the occurrence of other minerals in altered fractures such as monticellite ($CaMgSiO_4$), chabazite ($CaAl_2SiO_4.6H_2O$), analcite ($(NaAl_2O_6).H_2O$), artinite ($(Mg_2(CO_3)(OH)_2.3H_2O$, and hydromagnesite $Mg_5(CO_3)_4(OH)_2.4H_2O$ (all minerals identified by the writer by X-ray diffraction at VDMR laboratory) support a violent, steam-driven explosive event near the surface. The diatreme breccia pipe (2 feet in diameter) about 100 feet downslope along the quarry face from the drill site on top of the quarry is additional evidence for a high pressure-steam event. The light greenish breccia has an andesite matrix with casts of dolomite, black shale, and obsidian in a matrix of plagioclase, probably sanidine, hornblende, and biotite according to Rader and others (1986).

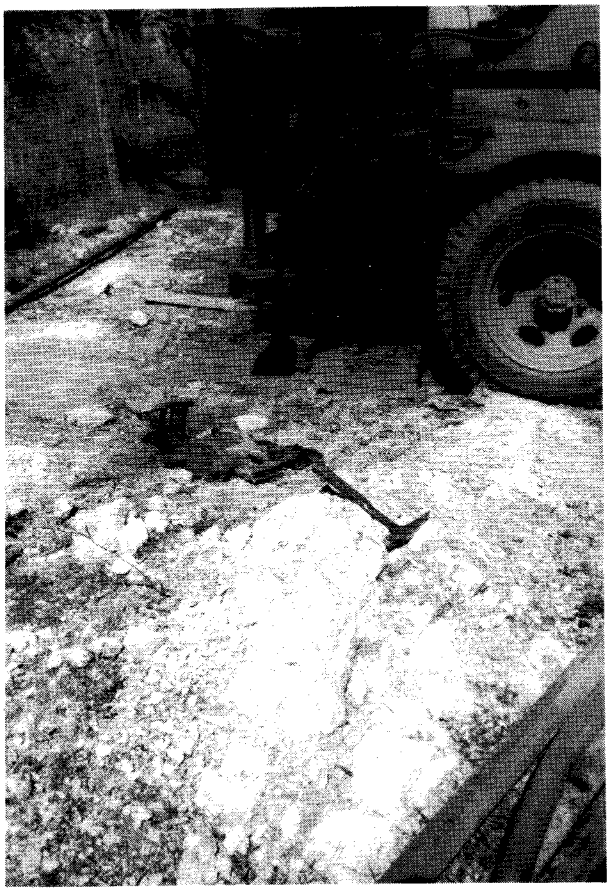
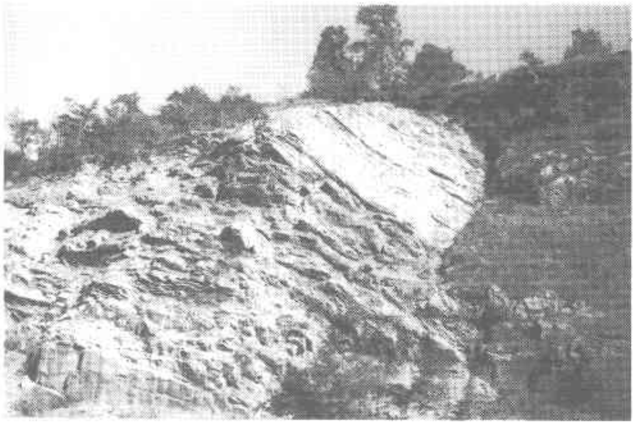


Figure 11. Brucite-calcite (predazzite) outcrop in contact with andesite dike and Beekmantown dolomite, top of Hightown quarry. Drill site for holes number 1 and 2.



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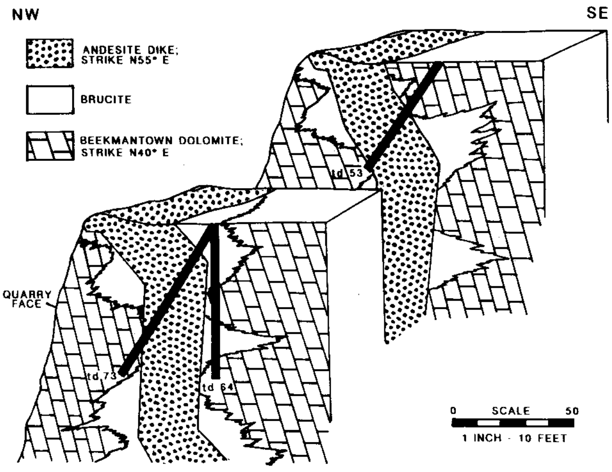

Figure 12. Interpretation of diamond drill results.

Brucite is only stable under very restricted temperature-pressure conditions (Figure 13). Note the small stable area for brucite plus calcite from 350-500°C at very low CO_2 pressures and high water pressures (800 to 1000 bars). Dolomite breaks down if carbon dioxide is able to escape to form calcite and periclase. Periclase than usually hydrates to form brucite. The phase equilibrium data suggests that a water rich-magma must be present under violent pressure to dedolomitize the rock and form periclase and brucite, but only if carbon dioxide can escape, presumably near the surface or with appropriate vents. Although confined to highly specialized environments, the occurrence of brucite is well-known in low temperature hydrothermal infiltration of magnesium-rich carbonate rocks. Brucite occurs in dolomite blocks near the throats or cones of volcanoes such as Vesuvius (Palache and others, 1944). There is no known evidence preserved of Eocene extrusive events such as flows or pyroclastic material turned to clays. The geomorphology does not indicate a Tertiary volcanic terrain and neither the Jurassic or Eocene dike swarms are radial. However, the radius or maximum elliptical axes of 10-15 miles for the dike swarms is more suggestive of slightly collapsed calderas that are rift-controlled than of the near-surface portions of single volcanic centers. Detailed seismic, gravity, and magnetic data might resolve this question.

Although drilling at Hightown quarry was very shallow and very limited and one can only speculate that there would be similar, and perhaps much larger alteration zones at relatively shallow depths, it seems clear that a much larger intrusive body than a 35 foot dike would be needed to generate the heat and water for a brucite contact zone large enough to produce a minimum of 100,000 tons of brucite-calcite marble. Brucite marble reserves, for example, are 20,000,000 to 30,000,000 short tons at Marble Canyon, Texas (R. McCreless, personal communication, 1990). Because of known alteration to brucite along two dikes to the north of Hightown quarry (cut by State Road 637), (Figure 4) further exploration in the area might be warranted. Brucite can easily be overlooked because of its white, gray, or bluish colors which easily blend in with the colors of dolomite or limestone.

Most of the mapped igneous dikes or plugs can be eliminated as exploration targets because their host rocks are not magnesium-bearing, that is, are not dolomite or dolomitic limestone. One larger known basalt intrusion with a rare varietal mineral for basalt, hercynite, occurs miles to the east of Hightown in Rockingham County (Figure 14). The olivine basalt intrusive at Mole Hill, west of Harrisonburg is 2000 feet by 1200 feet at surface and intrudes Lower Ordovician dolomite and limestone units of the Beekmantown Formation. The basalt contact with the dolomite is apparently everywhere covered by soil or scree (detached basalt boulders or cobbles that have moved down slope). Gathright and Frischman (1986) mapped the contact at a break in slope on the topographic map. The writer, in searching for a possible contact, noted an area at the base of the northeast corner of Mole Hill with old pits. Hand digging revealed under shallow soil cover chunks of black basalt with limestone clasts. Ten float samples were examined by X-ray diffraction, but none

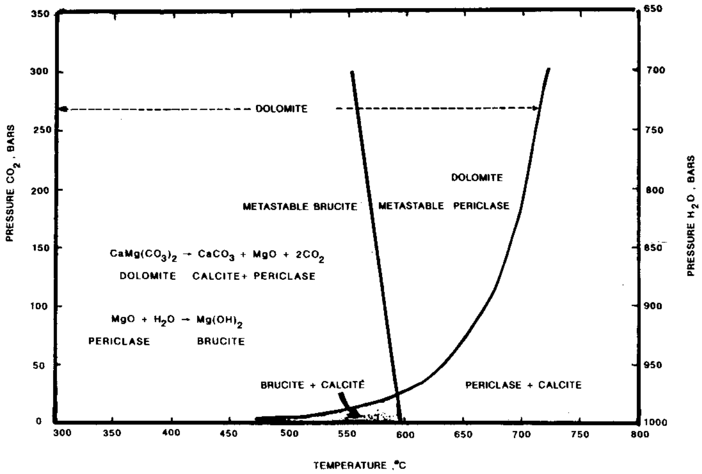

Figure 13. Stability of brucite, calcite, dolomite, and periclase in relation to temperature and pressure. Data from Turner (1968) and Winkler (1979).

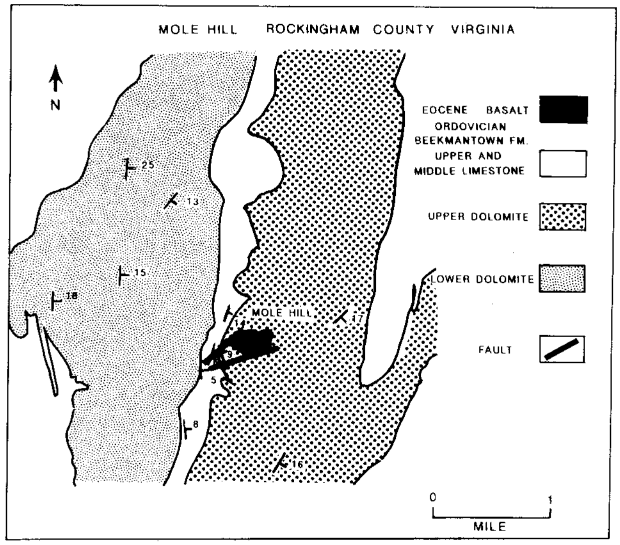

Figure 14. Geology in vicinity of Mole Hill, Rockingham County, Virginia. (After Gathright and Frischman, 1986).

of the white limestone clasts showed any brucite only calcite. However, both the limestone and dolomite units of the Beekmantown Formation dip at very low angles of 5-13° under Mole Hill and it is possible that the northeast corner is underlain by limestone not dolomite. The projected structure would appear to be very favorable for a basalt-dolomite contact near or at the surface. It is known from detailed gravity and magnetic data that the basalt intrusive extends east-west for 2300 feet and north south 1500 feet and dips north-northwest at 60 to 70 degrees (Elvers and others, 1967). It is of interest to note that a small, basaltic breccia body is indicated 2 miles north-northwest of Mole Hill (Johnson and others, 1971; Gathright and Frischman, 1986). Mole Hill might be worth further investigation by drilling as a target for brucite.

Diamond Drill Log
Hightown Quarry, Monterey 7 1/2 Minute Quadrangle
Highland County, Virginia
October, 1989
Logged by R.S. Good, Virginia Division of Mineral Resources
Charlottesville

DIAMOND DRILL HOLE NUMBER 1: NX core; vertical inclination; collar is on top of quarry, near middle, 34 feet southeast of quarry rim and 17 feet southeast of andesite dike contact. Collar starts on small outcrop of white, nearly white, very light gray to medium light gray massive, brecciated, calcite-brucite marble with 1-2 cm wide greenish gray to medium bluish gray veins of altered andesite making up 5% or less of outcrop. The andesite veins and veinlets fill fractures with a crude, but highly irregular, dislocated, northeast orientation.

0-1.5 feet: Lost core
1.5-26.5 feet: CALCITE-BRUCITE MARBLE (PRE-DAZZITE): very light gray to medium gray and medium light gray to nearly white, massive, with 1-2 cm greenish gray to medium bluish-gray veins of hydrothermally altered felsic biotite andesite with brown ankerite-hematite reaction rims; brecciated @ 9.0-10.0 with light gray to very light gray healed with white brucite-calcite fracture-fillings; fragmented at 24.0; thin section #1 2.2-2.4; #2 2.5-2.7 ft., disseminated and fracture fillings brucite in calcite; traces if black, carbonaceous veinlet fillings in trace amounts, with pyrite, apatite; XRD (BM-44) @ 3.0 calcite, brucite, hydromagnesite, artinite, stilbite, and serpentine (antigorite, chrysotile), bredigite (?); @4.0 ft., XRD (BM-2): calcite, brucite absent; @6.0 ft. XRD (BM-3): calcite, monticellite, serpentine group mineral, brucite absent; thin section #3 at 6.2-6.4 ft. and #4 at 6.8-7.0 ft.; @8.0 ft. XRD (BM-4): calcite, brucite; @9.8 ft., thin section #5; @ 10.0 ft., XRD (BM-5): calcite, brucite; thin section #6 @ 11.8-12.0 ft.; @ 12.0 XRD (BM-6): calcite and brucite; @13.8 ft., thin section #7; @ 14.0 XRD (BM-7): calcite and brucite; @ 15.8-16.0: thin section #8; @16.0 XRD (BM-8): calcite, dolomite, brucite; @ 17.8-18.0 ft., thin section #9; @ 18.0 XRD (BM-9): calcite, brucite, traces of clay and serpentine group minerals; @ 19.4-19.6 ft., thin section #10; @ 20.0 ft. XRD (BM-10): calcite, brucite, and dolomite; @ 22.0 ft., thin section #12; @ 22.0 ft. XRD (BM-11): calcite, brucite, dolomite, monticellite, and natrolite; @ 26.0 ft., thin section #13; @ 26.0 XRD (BM-13): calcite, dolomite, and monticellite; @ 26.3 ft., thin section #13.

26.5-41.0: BEEKMANTOWN FORMATION: medium light gray to medium gray, massive dolomite with hairline thickness, white calcite veining and fissure filling; @ 28.0 ft.: XRD (BM-14): dolomite @ 28.0 ft., thin section #16; @ 30.0 XRD (BM-15): dolomite with small amount (1-5%) brucite, and unidentified mineral with major peak @ 16.1 degrees; @ 30.0 ft., thin section #17; @ 32.0 breccia with black slicks and pyrite, thin section #18; @ 40.0 ft. thin section #19.

41.0-57.5: CALCITE-BRUCITE MARBLE (PRE-DAZZITE): @ 41.0 Beekmantown dolomite with white calcite-brucite veining; @ 42.0 white calcite-brucite marble with gray fragments up to 5-10 cm of unaltered dolomite; @ 42.0 thin section #20; @ 42.5 XRD (BM-16): calcite, dolomite, brucite, and serpentine group, trace; @ 44.0 thin section #21; @ 44.0 XRD (BM-17): calcite, brucite; @ 45.3 thin section #22; @ 49.0 ft. thin section #23, XRD (BM-18): calcite, brucite, monticellite, clinohumite (?); trace of quartz; @ 50.0 ft. thin section #24; XRD (BM-19): calcite, brucite; @ 53.0 ft., XRD (BM-20): calcite, brucite; @ 54.0 ft., thin section #25; @ 55.0 ft. XRD (BM-21): calcite, brucite; @ 56.0 ft., thin section #26; @ 57.0 XRD (BM-22): calcite, brucite.

57.5-64.0 BEEKMANTOWN FORMATION: 57.5 to 61.0 gray, medium gray, massive, calcareous, fractured dolomite (dolomitic limestone); 61.0-64.0: gray dolomite; @ 58.0 thin section #27; @ 60.0 thin section #28; @ 60.5, thin section #29, @ 61.0 XRD (BM-23): dolomite, calcite; @ 63.0 ft., thin section #30; @ 64.0 ft. XRD (BM-24): dolomite, with traces (1-3%) of calcite, scapolite, and quartz.

DIAMOND DRILL HOLE NUMBER 2: NX core; collar is about one foot northwest of collar of D.D.H. number 1. Inclination is 60 degrees at a direction of N35W or AZ 325 degrees, toward highwall of quarry. Hole starts on outcrop of white and very light gray, massive calcite-brucite marble with greenish-gray felsic andesite veinlets (<5%), 1-2 cm in width and less.

0.0-15.3 feet: CALCITE BRUCITE MARBLE, very light gray and white, massive, with greenish-gray andesite dikelets and veins @ 11.0-11.2 ft. and 15.0; @ 0.0 ft., XRD (BM-29): calcite, brucite; @ 2.0 ft., XRD (BM-28): calcite, brucite; @ 4.0 ft. XRD (MB-27): calcite, brucite, with traces of monticellite and serpentine group mineral; @ 6.0 ft. XRD (BM-26): calcite, brucite; @ 8.0 ft. XRD (BM-25): calcite and brucite; @ 10.0 ft. thin section #31; @ 13.0 ft. XRD (BM-30): calcite, brucite, and natrolite.

18.0-60.0: PORPHYRITIC BIOTITE ANDESITE: light gray with 3% black biotite phenochrysts av 1 mm, range 1-3 mm and 5% white laths of plagioclase averaging 6 mm length and ranging from 2-12 mm x 1 mm; @ 19.0 ft. XRD (BM-33): plagioclase (labradorite), pyroxene(pigeonite), biotite; @ 20.0 ft. thin section #34.

60.0-73.0 feet: BEEKMANTOWN FORMATION: dark gray andesite with breccia clasts of dolomite; @ 60.0 ft. thin section #35; @ 60.2 thin section #36; @ 62.0 thin section #37; @ 63.0 thin section #38; @ 63.0 XRD (BM-34): calcite, dolomite, and biotite; @ 66.0 ft. XRD (BM-37): dolomite and calcite; @ 67.0 thin section #40; @ 71.0 thin section #41; @ 71.0 XRD (BM-38): dolomite and quartz.

DIAMOND DRILL HOLE NUMBER 3: NX core; collar is 65 feet N50E along a N50E traverse line from D.D.H. 1 and 2. Inclination is 60 degrees from horizontal @ direction of N55W.

0-15.0 feet: No core recovery. Overburden or badly weathered.
16.0-16.5: BEEKMANTOWN FORMATION: yellowish gary to very pale orange dolomite.
@ 15.0 ft. XRD (BM-39): dolomite and quartz; @ 15.0 thin section #42;
16.5-23.5: PORPHYRITIC BIOTITE ANDESITE: medium light gray with 3% biotite phenochrysts (1-3 mm) and 5% plagioclase phenochrysts (2 x 12 mm and 10-15 mm rhombs.
23.5-26.0: lost core
26.0-44.0: PORPHYRITIC BIOTITE ANDESITE: gray to medium gray with black 1-3 mm biotite chrysts and cream colored 2-12 mm x 1-2 mm laths and 10-15 mm rhombs; @ 35.0 ft., thin section #44; @ 42.0 XRD (BM-41): plagioclase, biotite, pyroxene @ 43.0 dolomite clast: XRD (BM-42): dolomite, calcite.
44.0-47.0; BEEKMANTOWN FORMATION: gray to medium light gray dolomite breccia; @ 44.0 thin section #45 at contact of dolomite and andesite 47.0 feet bottom of hole; @ 47.0 thin section #46.

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GEOLOGY, GEOCHEMISTRY AND PHYSICAL CHARACTERIZATION OF MINNESOTA CLAYS

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ABSTRACT

Minnesota has a variety of clays and shales that have potential as industrial clays. These clays are: 1) Precambrian clays; 2) Paleozoic shales; 3) pre-Late Cretaceous primary (residual) and secondary kaolins; 4) Cretaceous ball clays and marine shales; and 5) glacial and recent clays. Clays are currently used for brick and as a portland cement additive. Other possible uses currently being investigated include filler and coating grade kaolins, ceramic tile, refractory products, lightweight aggregates, sanitaryware, and livestock feed filler.

Precambrian clays occur in the 1.1 Ga Keweenawan interflow sediments of the North Shore Volcanic Group, the Middle Proterozoic Thomson Formation and in the Paint Rock member of the Biwabik Iron-Formation on the Mesabi Iron Range, all in northeastern Minnesota. The Paint Rock clays have potential as red coloring additives and glazes.

Paleozoic shales in southeastern Minnesota are primarily kaolinitic and illitic shales that are interbedded with limestones. The Ordovician Decorah and Glenwood Shales are marine shales that, in the past, have been used to make bricks, tile, and lightweight aggregate. The thickness of these shales ranges from 10-140 feet. The Decorah Shale has the lowest firing temperature with the best shrinkage and absorption characteristics of all the Minnesota clays.

The pre-Late Cretaceous primary and secondary kaolins are found in the western and central portions of Minnesota; the best exposures are located along the Minnesota River Valley and in the St. Cloud area. The primary or residual kaolinitic clays are the result of intense weathering of Precambrian granites and gneisses prior to the Late Cretaceous. Subsequent reworking of these residual clays led to the development of a paleosol and the formation of pisolitic kaolinite clays. Weathering of the primary kaolins produced fluvial/lacustrine (secondary) kaolinitic shales and sandstones. Recent exploration activity is concentrated in the Minnesota River Valley where the primary kaolin thickness ranges from 0 to 200+ feet and the thickness of the secondary kaolins ranges from 0-45+ feet (Setterholm and others, 1989). Similar kaolinitic clays occur in other areas of Minnesota. However, less information is available on their thickness, quality and areal distribution due to varying thicknesses of glacial overburden. Cement grade kaolin is extracted from two mines in the Minnesota River Valley, and a third mine there yields secondary kaolins that are mixed with Cretaceous shales to produce brick.

During the Late Cretaceous, Minnesota was flooded by the transgressing Western Interior Sea, which deposited both non-marine and marine sediments. These sediments are characterized by gray shales, siltstones, sandstones, and lignitic material. Significant occurrences of Cretaceous sediments are found throughout the western part of the state, with the best exposures located in Brown County, the Minnesota River Valley, and the St. Cloud area. In Brown County, the maximum thickness of the Cretaceous sediments is >100 feet. These sediments thicken to the west and can be covered by significant thicknesses (>300 ft.) of glacial overburden in many areas. Current brick production comes from the Cretaceous shales in Brown County. In the past, the Red Wing pottery in Red Wing, Minnesota, used Cretaceous and some Ordovician sediments to produce pottery, stoneware and sewer pipe.

Glacial clays occur in glacial lake, till, loess and outwash deposits and these clay deposits range in thickness from 5 to 100+ feet. Much of the early brick and tile production (late 1800s and early 1900s) in Minnesota was from glacial clays. The last brickyards, e.g., Wrenshall in northeastern Minnesota and Fertile in west-central Minnesota, to produce from glacial lake clays closed in the 1950s and 1960s. There has also been some clay production from recent fluvial and lake clays that have thicknesses of 2-10+ feet. Both recent and glacial clays are composed of glacial rock flour with minor quantities of clay minerals. Carbonates can be a significant component of many of these clays. Glacial lake clays in northwestern Minnesota (glacial Lake Agassiz - Brenna and Sherack Formations) begin to bloat at 1830° F due to the presence of dolomite. These clays are a potential lightweight aggregate resource.

INTRODUCTION

CLAY DISTRIBUTION

Clays in Minnesota occur in Precambrian to Pleistocene age rocks. Clays deposited during the last glacial epoch represent the largest surface exposure in Minnesota. These clays are represented by till, lake, outwash, and loess deposits. Glacial till, lake and outwash deposits occur throughout the state while loess is concentrated in the southeast and southwestern corners of the state.

Underlying the glacial clays, particularly in the western and central portions of Minnesota, are Late Cretaceous shales of the Greenhorn stage of the Cretaceous Western Interior Seaway. Prior to the Late Cretaceous transgression, an intense period of weathering produced primary and secondary (fluvial/lacustrine) kaolinitic clays. While these clays have a wide distribution throughout Minnesota, they are minimally exposed. The best exposures are in the Minnesota River Valley in southwestern Minnesota and in the St. Cloud area in central Minnesota (Figure 1).

Paleozoic clays crop out only in southeastern Minnesota. The Paleozoic clays in northwestern Minnesota are covered by several hundred of feet of Pleistocene and Cretaceous sediments. Of the Paleozoic clays, the shales in the Ordovician Decorah and Glenwood Formations have the best thicknesses and physical characteristics for industrial uses.

Some Precambrian clays occur in the Paint Rock Member of the Biwabik Iron-Formation on the Mesabi Iron Range of northeastern Minnesota, in the argillaceous Thomson Formation and in Keweenawan sediments along the north shore of Lake Superior. However, very few usable Precambrian clays exist.

Recently, 499 samples were collected under a program funded by the Legislative Commission on Minnesota Resources (Figure 1; Hauck and others, in prep.). The purpose of this project was to determine the geological, geochemical, mineralogical and physical characteristics of the different clays found throughout Minnesota Samples were collected in 65 of Minnesota's 87 counties. The physical tests conducted on these clays were X-ray mineralogy, cation exchange capacity, particle size analysis, Munsell color, and firing characteristics (firing range, shrinkage, absorption and color). A regional drilling program and kaolin processing research was also conducted as a part of this program (Setterholm and others, 1989; and Prasad and others, 1990).

PREVIOUS WORK

The earliest work on the potential commerical characteristics of clays in Minnesota was reported by Grout and Soper (1919). They principally described the location, type of clay product (if any), production figures and firing characteristics of many clays in use in Minnesota then. Follow up clay studies were conducted by Grout (1947), Bradley (1949), Riley (1950), Prokopovich and Schwartz (1957), Parham and Hogberg (1964), Parham and Austin (1969), Parham (1970), Haas and others (1987) and Heine and Hauck (1988). Riley (1950) and Prokopovich and Schwartz (1957) specifically studied the bloating properties of the clays for use as lightweight aggregate.

PREVIOUS AND CURRENT CLAY PRODUCTION

Nearly every county in Minnesota, at least since 1860, had a clay production facility or tried to produce clays (Grout, 1947). Examination of the Minnesota Census (1860-1890) and Minnesota Business Gazetteer (1860-1924) suggested that at the turn of the century there were more than 300 clay production or clay-related facilities, i.e., distribution centers. One of the largest non-brick clay users were the pottery, stoneware and sewer pipe companies that operated in Red Wing, Minnesota from 1855 (bricks were produced at first) until the last pottery closed in 1967 due to a labor dispute (Tefft and Tefft, 1981). With the closure of the Wrenshall brickyards in 1953 (Heine and Hauck, 1988), the Ochs Brick and Tile Company in Springfield, Brown County, the Fertile brickyard in Polk County, and the Twin City brickyard in St. Paul were the last of the few operating major clay producers within the state. With the closure of the Twin City and Fertile brickyards in the early- to mid-1960s, only the Ochs Brick and Tile Company produced clay for industrial use. Recently (1986 and 1988), two new clay mines, i.e., the Northwest States Portland Cement Company of Mason City, Iowa and the Northern Con-Agg Company of Maple Grove, Minnesota, respectively, have produced residual kaolinitic clays for an additive to portland cement (Figure 2).

ACKNOWLEDGEMENTS

Data collection and support for this project was supplied by a grant from the Legislative Commission on Minnesota Resources. Access to mine facilities and other data were graciously provided by the Ochs Brick and Tile Company, Springfield, Minnesota, the Northwest States Portland Cement Company, Mason City, Iowa, Northern Con-Agg, Incorporated, Maple Grove, Minnesota, Nova Natural Resources Corporation, Denver, Colorado, Meridian Aggregate Company, St. Cloud, Minnesota, Mayor Hugh Line and the City of Wrenshall, MN, Mr. C. Firle of Fairfax, MN, Mr. W. Munsell of Franklin, MN, and Mr. G. Peterson and family, Zumbrota, MN.

GEOLOGY

PRECAMBRIAN CLAYS

Precambrian clays in Minnesota are found in the interflow sediments (shales and siltstones) of the 1.1 Ga Keweenawan North Shore Volcanic Group and the argillaceous rocks of the Middle Proterozoic Thomson Formation and the Lower Proterozoic Paint Rock Member of the Biwabik Iron-Formation. Of these three clays, the Paint Rock clays have the best potential as industrial clays. The mineralogy of the Paint Rock clays is kaolinite, illite, and hematite. The clays are considered waste material during the mining of iron ore. Due to the high iron content of these clays, these clays are being tested as possible color additives or as a glazing material (Toth and others, 1990).

PALEOZOIC SHALES

The Paleozoic rocks of Minnesota are largely confined to the southeastern portion of the state, although rocks of Ordovician age underlie thick glacial cover in the northwest corner of the state (Figure 2). The Paleozoic rocks in southeastern Minnesota were deposited in a shallow marine sea about 550 million years ago. Their depositional extent was limited to the north and east by Precambrian rocks of the Wisconsin Arch and to the west by the Transcontinental Arch (Austin, 1972; Ojakangas and Matsch, 1982). Alternating transgressions and regressions of the sea were responsible for the Cambrian and Ordovician sandstone-shale-carbonate stratigraphy in this area (Figure 3). Only three Paleozoic shale units were investigated: the late Cambrian St. Lawrence For-

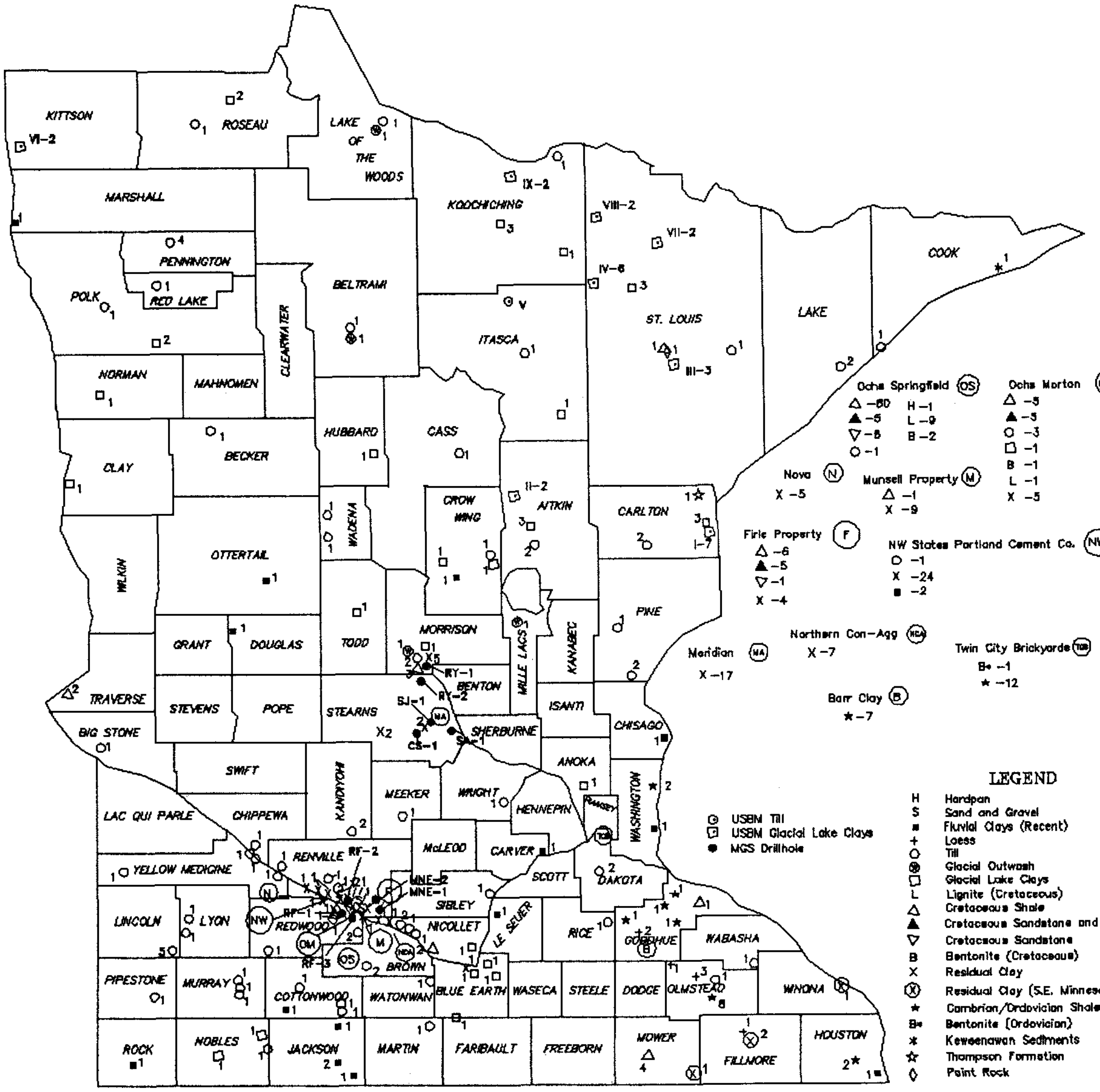

Figure 1. Sample locations of clay samples collected during 1987 and 1988.

mation and the Ordovician Glenwood and Decorah Formations.

Of these three Paleozoic formations, the Ordovician Decorah Formation historically provided the largest volume and the best raw material for the manufacturing of clay products (brick, tile, sewer pipe, etc.). The Twin City brickyard in St. Paul used Decorah shale to produce brick and tile. The Glenwood Formation, because of its limited thickness (ave. 5 ft. versus 45-90 ft. for the Decorah), was used to a much lesser extent in ceramic applications. The only significant use of the St. Lawrence Formation was when the formation was quarried in Fillmore County, primarily for its carbonate content; the shaly portions were mixed with quarry refuse and used as road material (Grout and Soper, 1919).

The late Cambrian St. Lawrence Formation has two members, the Black Earth and the Lodi. Samples come only from the more shaly Lodi member. The Lodi member consists primarily of thin to thick-bedded, argillaceous, silty dolomite (Austin, 1972), containing illite and mixed-layered clays.

The Ordovician Glenwood Formation is a somewhat thin (2-16 ft.) unit of argillaceous sandstone and shale (Webers, 1972). The Glenwood, like the St. Lawrence, is composed primarily of illite (Parham and Austin, 1972; this study).

The Decorah Formation varies in thickness from about 25 feet in the southeast in Fillmore County to about 90 feet in the north in the Twin Cities area (Parham and Austin, 1969). The Decorah is a fossiliferous, greenish-gray marine shale containing scattered, thin carbonate layers (limestone) in its lower portions, which increase both in thickness and frequency toward the top. A thin (0.75-1.5 inch) layer of potassium bentonite (the Millbrig K-bentonite) is also present within the basal portion of the Decorah at many localities (Parham and Austin, 1969). Kaolinite is the major clay min-

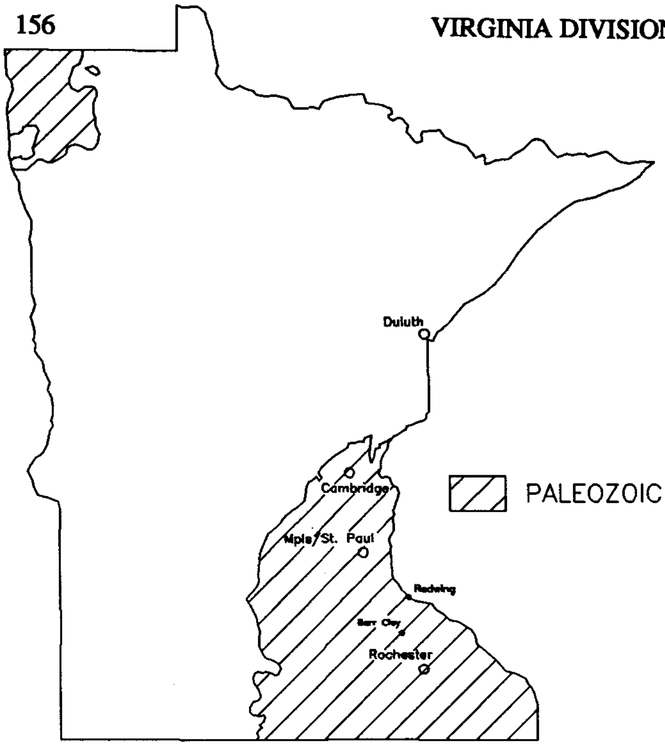

Figure 2. Distribution of Paleozoic rocks in southeastern Minnesota (after Ojakangas and Matsch, 1982).

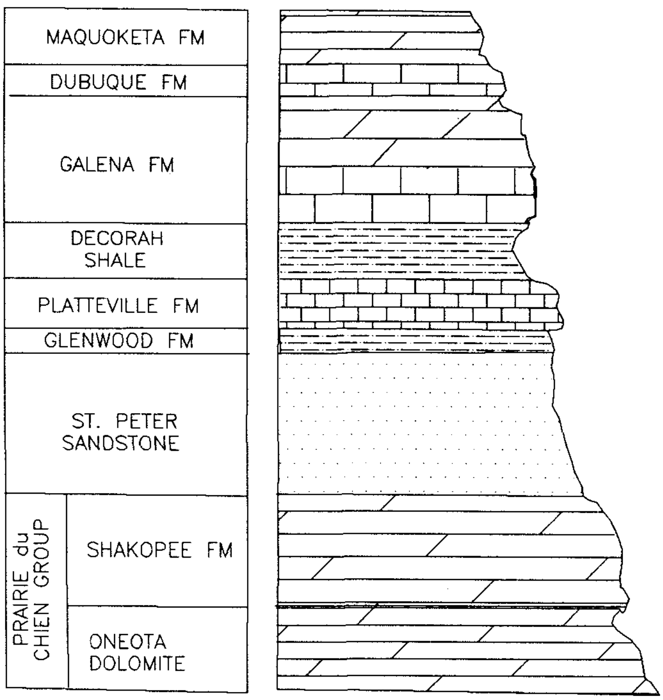

Figure 3. Stratigraphic section of Ordovician rocks in southeastern Minnsota (after Ojakangas and Matsch, 1982).

eral with minor illite. However, the kaolinite content decreases from the southwest toward the northeast where illite becomes the dominant clay mineral (Parham and Austin, 1969). This change in clay mineralogy, according to Parham and Austin (1969), is due to erosion of either pre-existing kaolinitic sedimentary rocks or from a kaolinitic-rich saprolite.

PRIMARY AND SECONDARY KAOLINS

Underlying the Pleistocene and Late Cretaceous sediments in western and central Minnesota are pre-Late Cretaceous primary (residual) and secondary kaolinitic clays. The clay content of the saprolite or residual clays is dependent on the composition of the bedrock and the degree of weathering. The bedrock in the Redwood Falls area is the Archean (3.5 Ga) Morton gneiss, which has granitic gneisses (adamellite to granite), tonalitic to granodioritic gneisses and amphibolites (Goldich and others, 1980). The tonalitic to granodioritic gneisses are primarily composed of biotite, quartz, oligoclase, microcline and minor hornblende and hypersthene (Goldich, 1938; Goldich and others, 1980), whereas the amphibolite is composed of clinopyroxene, hornblende and plagioclase (Lund, 1956). The granitic rocks are composed of quartz, microcline and plagioclase with minor biotite (Goldich and others, 1980).

In general, the residual clays are composed of two types; a white to light greenish-yellow kaolinitic clay and a green, chlorite-rich clay. The kaolinitic saprolite is composed of kaolinite and quartz. Some feldspar may still be present near the unweathered bedrock contact. Residual gneissic textures or primary porphyritic textures may still be visible in the saprolite. In most areas, a 2-6 foot iron-stained zone occurs below the Cretaceous-pre-Late Cretaceous or the Cretaceous-Pleistocene contacts. The iron-staining formed from groundwater precipitation of iron oxides moving along topographic/hydraulic gradients. Excellent exposures of the residual clays occur at the Northwest States Portland Cement mine (NWSPC), the Northern Con-Agg mine and the Meridian Aggregate mine (Figures 4-9).

The secondary kaolinitic clays are derived by weathering of the residual clays. These clays are pisolitic at or near the residual or upper secondary (paleosol ?) contacts, or they are sandy or silty. Lignitic lenses are present within the secondary clays. Lignitic "trash" also occurs in kaolinitic sand channels. The secondary clays have been deposited under fluvial/lacustrine conditions and have been subjected to continued lateritic weathering, i.e., pisolite formation. Excellent exposures of the secondary clays are present in the Ochs' Morton mine (Figure 10).

The NWSPC Mine, Redwood Falls, MN

The NWSPC mine now includes two other pits, i.e., the old and new Nova Natural Resources mines, which are on adjacent property. These mines are located on the south side of the Minnesota River Valley, east of Redwood Falls (Figure 4). NWSPC mines the saprolite for use in portland cement. The mine contains approximately eighty feet of saprolite. The clays are shipped by truck and rail to Mason City, Iowa.

The stratigraphy in the mine is composed of Pleistocene, Cretaceous, and pre-Late Cretaceous sediments (Figure 5). The clay minerals in the mined residual clay are kaolinite with minor chlorite, illite and trace mixed-layered clays. The clay mineralogy of residual chloritic pods (biotite gneiss and amphibolite) within the weathered Morton gneiss is chlorite and kaolinite with minor illite and mixed-layered clays.

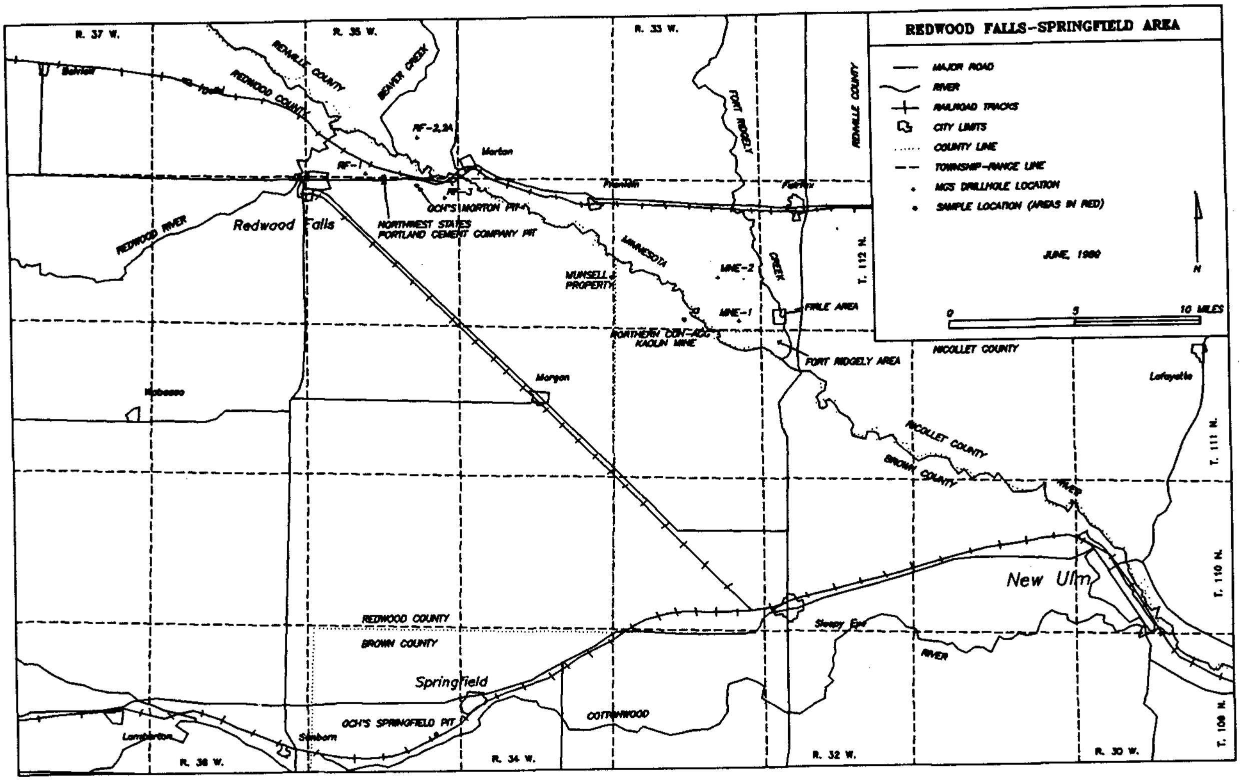

Figure 4. Redwood Falls area location map.

The Northern Con-Agg Mine, NW Brown Co., MN

The stratigraphy in the mine is composed of recent (post-Pleistocene) fluvial sediments, saprolitic Morton gneiss with xenoliths of amphibolite and a saprolitic mafic dike (Fig.ure 6). The clays are kaolinite with minor illite. Very little chlorite is present. The clays have a yellow iron staining at the contact with the overlying Pleistocene fluvial sediments (glacial river Warren ?). The mine currently contains approximately 40+ feet of saprolite, which is shipped to Mason City, Iowa.

Firle Property, Fairfax, MN

The kaolinite occurrences on the Firle property (Figure 4) are in saprolite of the Fort Ridgely Granite (Lund, 1956). Overlying the saprolitic Fort Ridgely Granite are glacial and Cretaceous sediments (Figure 7). The Pleistocene sediments consist of sand and gravel. The Cretaceous shales and sandstones are similar to other Cretaceous sediments in the Minnesota River Valley. A pisolitic kaolinitic clay is interbedded with these shales and sandstones. This secondary kaolinitic clay is commonly found between the residual material and the Cretaceous shales in other parts of the Minnesota River Valley. The deposition of this pisolitic kaolinite is probably the result of local variations in the source area, possibly the reworking of a pisolitic kaolinite, or it may represent a stream lag deposit material.

Secondary kaolinites are absent on the Firle property, but are found further to the west in Minnesota Geological Survey drill hole MNE-1 (Figure 4; Setterholm and others 1989). The kaolinitic shale and sandstones in this drill hole comprise several coarsening upward sequences. The change from secondary kaolinite deposits to later Cretaceous sediments is sharp and is disconformable in most areas of the Minnesota River Valley. The environment of deposition for both Cretaceous shales and the secondary kaolinitic material is fluvial/lacustrine.

The residual kaolinitic clays on the Firle property are significantly different from other exposures in the Minnesota River Valley. The Fort Ridgely Granite is a pink to grey, medium to coarse grained, porphyritic granite with aligned feldspar phenocrysts (Lund, 1956). Mafic inclusions are usually small and locally abundant. Another significant difference is the presence of a large quartz vein and many associated smaller veins throughout the Firle property. The Fort Ridgely Granite may have been fractured and hydrothermally altered during emplacement of the quartz veins. Some of the original kaolinite formation on the Firle property is the result of hydrothermal alteration that occurred prior to weathering. The fracturing and hydrothermal alteration also made the subsequent chemical weathering more effective in the formation of kaolin.

Meridian Aggregates' Mine, St. Cloud, MN

The stratigraphy in the Meridian mine is composed of unweathered granite and mafic dikes, saprolite, and glacial sediments (Figures 8 and 9). The saprolite/granite contact is well exposed, vertically variable, and gradational. The sap

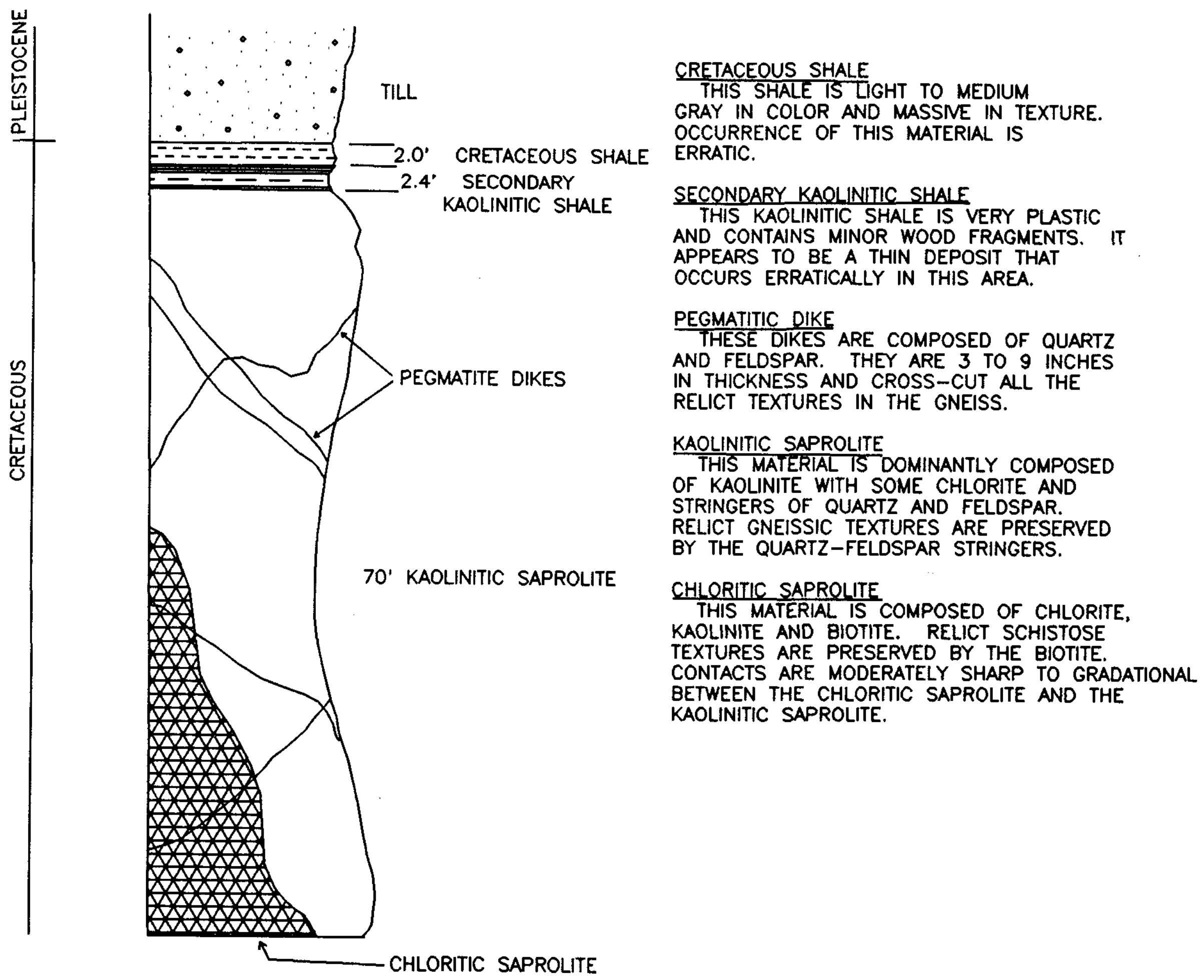

Figure 5. Northwest States Portland Cement mine stratigraphic section, Redwood County.

rolite is approximately 40-50 ft. thick and is removed as waste material so that the granite can be quarried for aggregate. The contact with the glacial sediments (gravel and till deposits), is sharp. Within the glacial sediments is a thin secondary kaolinitic-rich unit.

The granitic bedrock is a part of the Stearns Granitic Complex (Goldich, 1968; Morey and others, 1982; Dacre and others, 1984). The "red" and "gray" granites that are, or have been, mined in the Meridian pit belong to the Stearns Granitic Complex. The "gray" granite is a granodiorite composed of quartz, plagioclase, microcline, biotite and hornblende (Keighin and others, 1972). The "red" granite is mainly composed of quartz, microcline and plagioclase (Keighin and others, 1972).

The compositional variability of the felsic and mafic parent rocks and the degree of weathering produces a variable clay assemblage in the saprolite. The whitest clay is associated with the most felsic composition of the granites and the greenest with the mafic dikes. The residual clays in some areas of the mine have been removed by glacial and preglacial processes. Slickenslides and other textures support the presence of faulting. These pre-weathering faults provided conduits for groundwater and therefore, allowed deep, variable weathering of the bedrock.

Ochs' Morton Mine, Morton, MN

The mine has two pits, East and West. The East pit is now reclaimed. The stratigraphy in these pits includes Pleistocene, Cretaceous, pre-Cretaceous, and saprolitic Precambrian rocks (Figure 10). More than 80 feet of Pleistocene glacial till and outwash sediments overlie the Cretaceous and pre-Cretaceous sediments. The Cretaceous shales and sandstone range from 10 to 20+ ft. thick and were eroded during glaciation.

The protolith of the kaolinitic saprolite is the Morton Gneiss. This saprolite is the same composition as the saprolite being mined at the NWSPC mine. In the West pit, some of the saprolite is pisolitic below the contact with the overlying secondary kaolinitic sediments. The pisolites in the saprolite are poorly formed, and are found in the upper 6 to 10 inches when present.

The secondary kaolinitic sediments consist of interbedded kaolinitic shales and sandstones, which are commonly pisolitic. In the East pit, lignite and lignitic shale is interbedded with these sediments at the contact with the overlying Cretaceous shales. Correlation of the sandstones and shales between the East and West pits is difficult due to the fluvial depositional environment. In addition, some pisolitic and

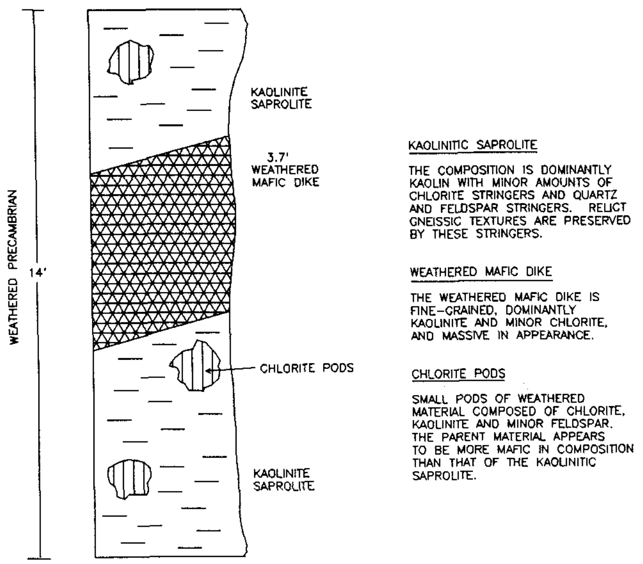

Figure 6. Generalized stratigraphic section of the Northern Con-Agg kaolin mine, Brown County.

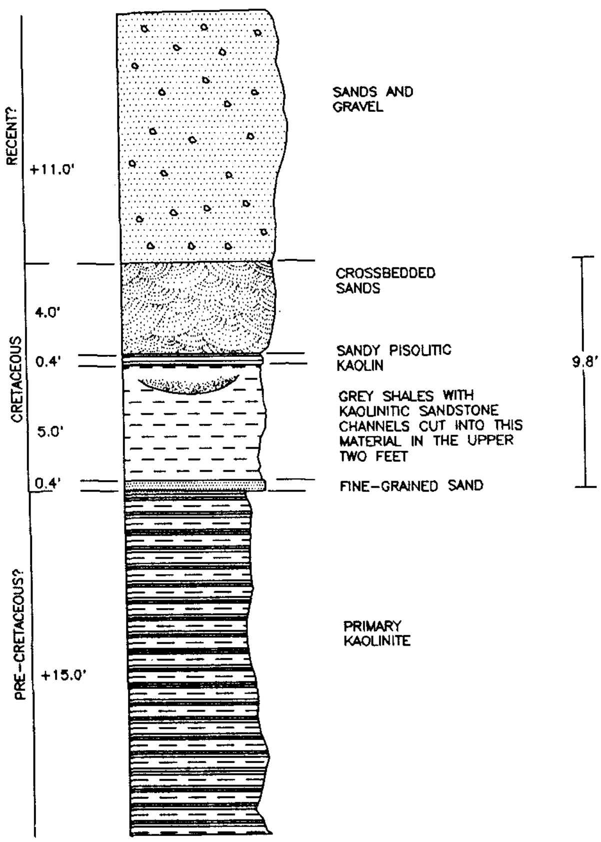

Figure 7. Stratigraphic section of Late Cretaceous rocks on the Firle property, Renville County.

brecciated textures suggest periods of emergence.

Only the secondary kaolinites are mined for making brick. The 2 micron size fraction of the secondary clays consists of kaolinite with trace amounts of gibbsite, illite and mixed-layered clays. The Al_2O_3 content of the secondary clays ranges from 30-40%. However, the silica content of the clays is highly variable due to changes in fluvial depositional conditions.

CRETACEOUS SHALES

During the Late Cretaceous most of western and central Minnesota was inundated by the Western Interior Sea (WIS; Austin, 1972). Both marine and non-marine sediments were deposited during the transgression and regression of the WIS (late Cenomanian - Greenhorn cycle, Unit 2; Shurr and others, 1987).

The best exposures of these Cretaceous sediments are in and around the Minnesota River Valley. Clay is mined in the Ochs Brick and Tile mine near Springfield, Minnesota (Figure 4) to make bricks. The Cretaceous clays in this mine represent the thickest, contiguous section of currently exposed Cretaceous sediments in Minnesota, i.e., 60.5 feet.

Ochs' Springfield Mine, Springfield, MN

The stratigraphy in the Springfield mine consists of Cretaceous shale, siltstone, sandstone, lignitic sediments, hardpan, and Pleistocene glacial drift (Table 1 and Figure 11). The Cretaceous sediments are subdivided into twenty-five subunits that are grouped into five major stratigraphic units (A, B, C, D, and E - Figure 11). The mine operates on two 30 foot benches. The upper bench contains units A, B and the upper part of C. The lower bench contains units D, E and the remainder of C. Units A and B are not currently mined due to their high sulfur content in the form of gypsum and pyrite.

The stratigraphy in the Springfield mine indicates that the sediments were deposited in a fluctuating and evolving near shore environment. Unit E represents the upper portion of a prograding deltaic sequence. Within Unit D are three fining upward sequences; subunits D7 and D6, subunits D5 and D4, and subunits D3 through D1. The D7-D6 sequence represents a change from fluvial to more paludal conditions, based on the increase in lignitic material. These three fining upward sequences are produced by a migrating transportation source, such as a delta, that deposited these sediments into a standing body of water. Sloan (1964) originally proposed a deltaic-lacustrian origin for the upper units.

The basal subunits, C5 and C4, also represent a fining upward sequence that reverses in subunit C3 and C3S to an upward coarsening sequence. A second coarsening upward sequence occurs in subunits C2, C1, and C1S. These changes in style of deposition are also attributed to the same migration of the transporting source, i.e., a deltaic environment.

A major depositional change occurs in Unit B, with the formation of the lignite sequence. The presence of abundant lignitic material and broad, thin sands represent a paludal or estuarine environment. Unit A represents a near shore marine

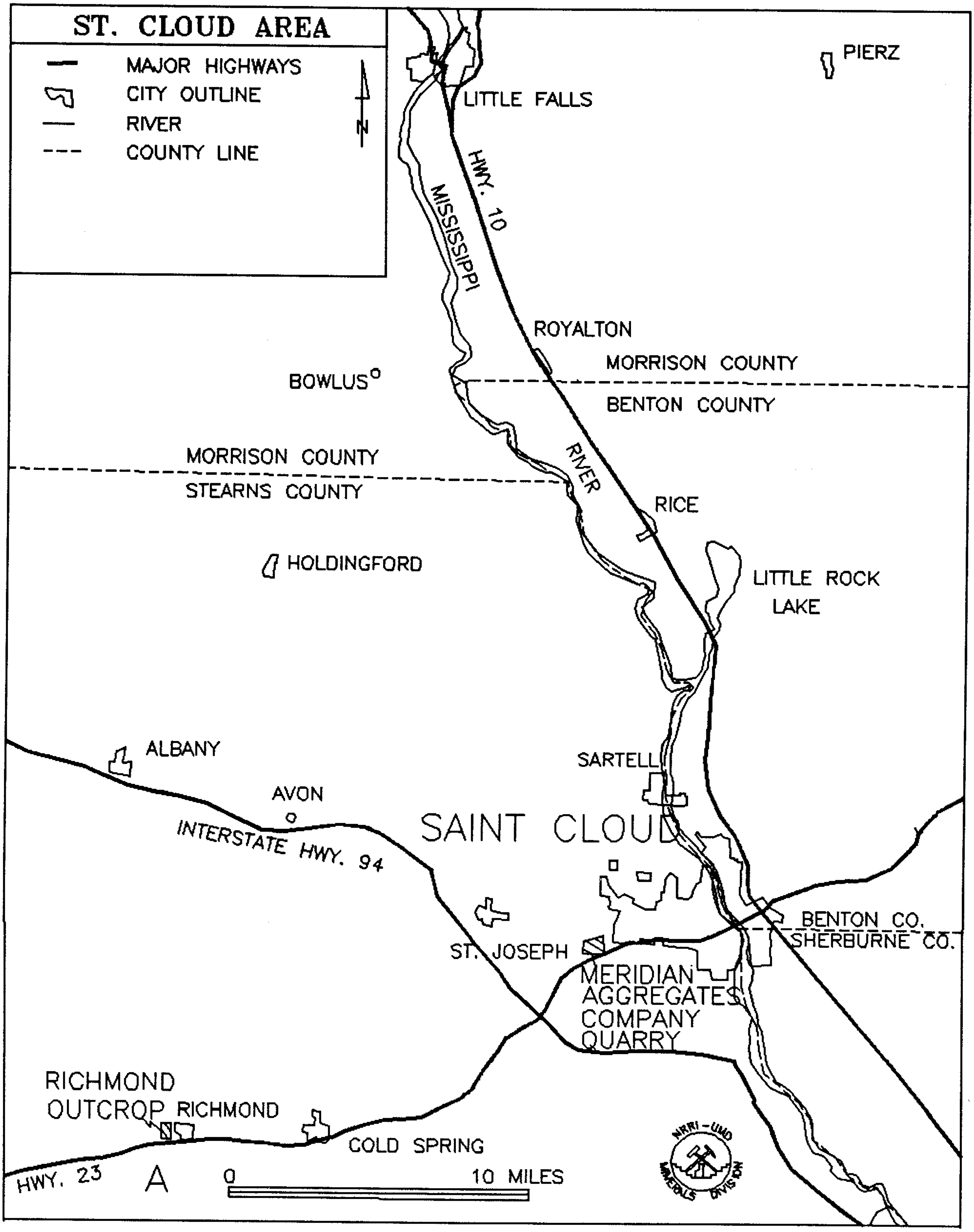

Figure 8. St. Cloud area location map, Stearns, Morrison, Benton, and Sherburne Counties.

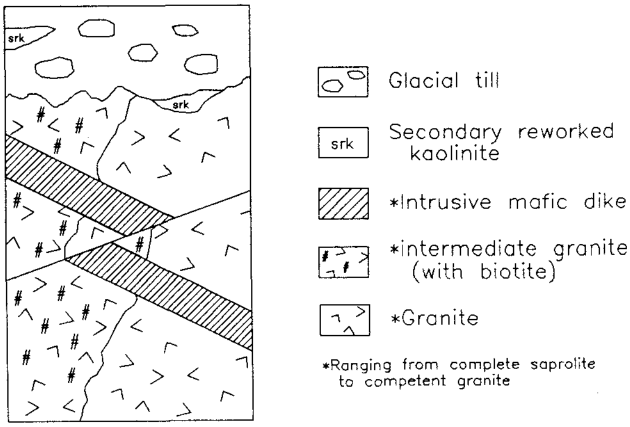

Figure 9. Meridian Aggregates' St. Cloud mine - generalized stratigraphic section (no scale implied).

Table 1. General Stratigraphy of the Ochs Brick and Tile mine, Springfield, Minnesota (after Heine and Hauck, 1989)

Marine Sequence

Unit A - interbedded shales and sandstone - 7.0 ft.

Deltaic Sequence

Unit B - lignitic (coal) sequence - 2.1 ft.
Unit C - 3 upward coarsening sequences - 32.1 ft.
Unit D - 3 upward fining sequences - 14.6 ft.
Unit E - interbedded shale and sandstone (foreset beds) - 3.9+ ft.

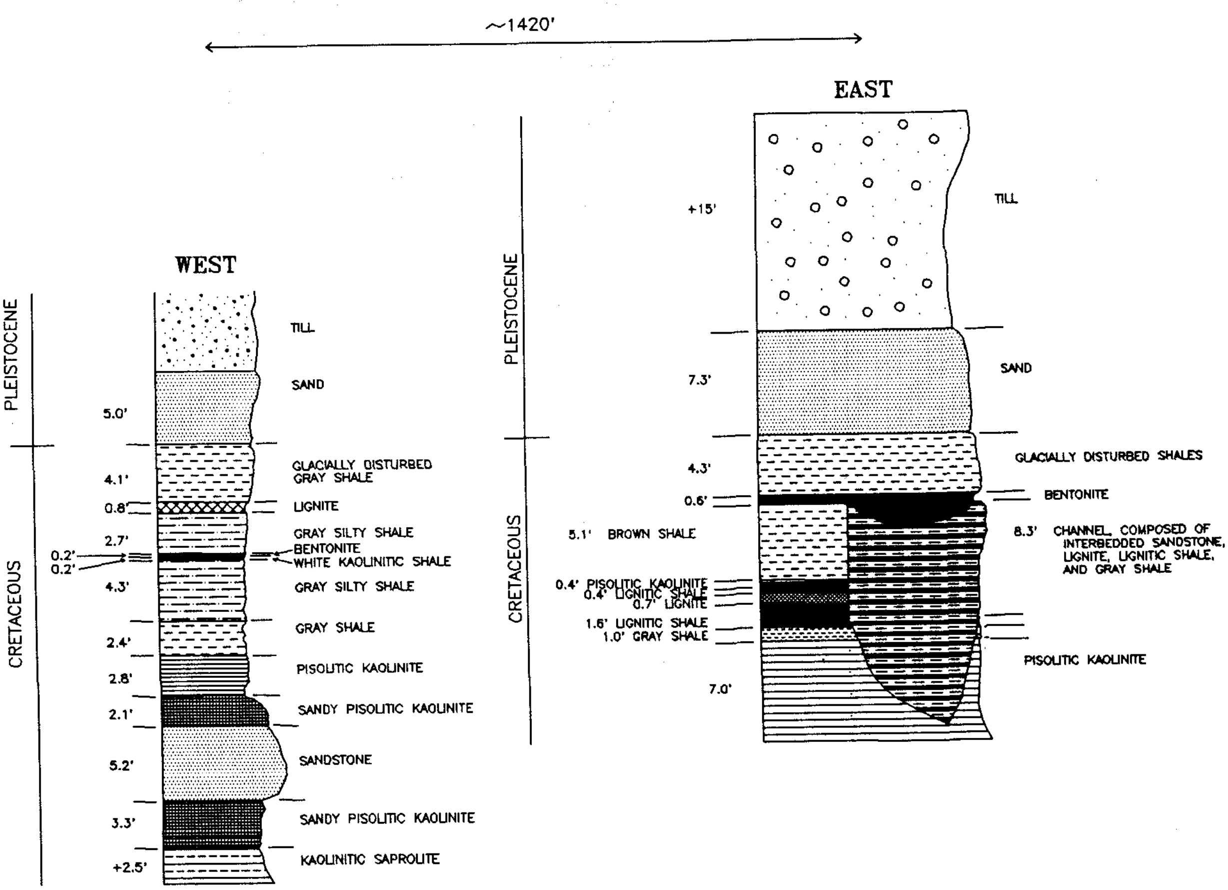

Figure 10. Ochs Brick and Tile Company Morton mine - East and West pit stratigraphic sections (looking north).

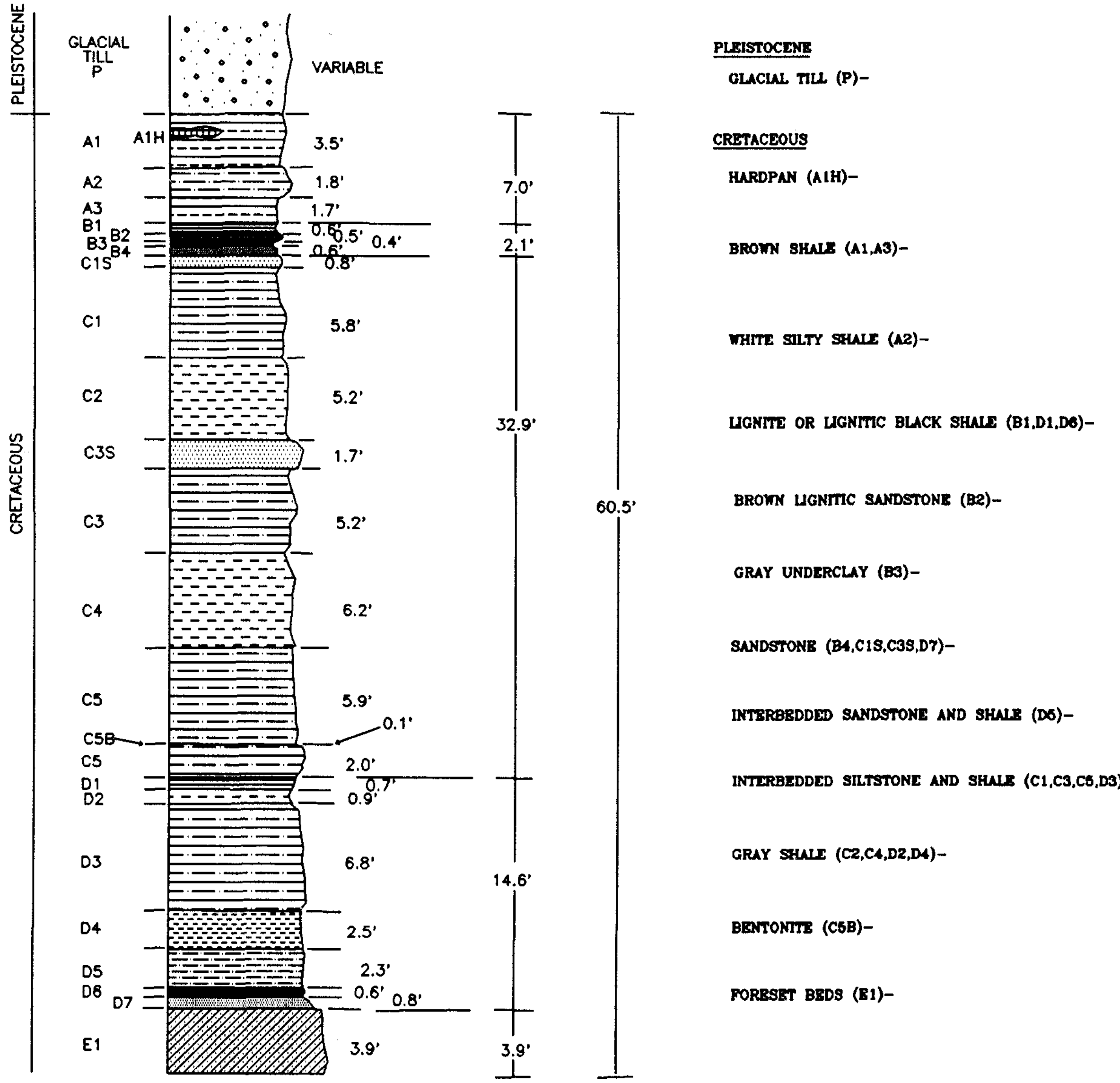

Figure 11. Stratigraphic section of the Late Cretaceous rocks in the Ochs Brick and Tile Springfield mine, Brown County.

environment. Sloan (1964) suggests that the units in the upper mine bench represent a transition from non-marine or estuarine into marine conditions. The stratigraphy represented in the lower mine bench is consistent with the continuation of a non-marine or estuarine depositional environment.

Other Cretaceous Clays

Other good exposures of Cretaceous sediments within the Minnesota River Valley crop out in the Ochs' Morton mine (Figure 10) and on the Firle property (Figures 4 and 7), but these shales have no commercial value at the present. Within the Cretaceous sediments at the Ochs' Morton mine is a thin (ave. 2 in.) green to dark green bentonite (smectite; Figure 10). This bentonite is mineralogically different from the C5B subunit in the Springfield mine, and this bentonite lies directly above the secondary kaolinite section. Still, the regional extent and thickness of this unit has yet to be established.

In the St. Cloud area, the Cretaceous section is presently exposed in the Richmond area (Figures 8 and 12). These shales are again carbon-rich shales that contain gypsum and are similar to Unit B in the Ochs' Springfield mine, but the Richmond section is thicker and less sandy. However, like the Springfield shales, some of these shales have excellent firing characteristics and mining thicknesses (Toth and others, 1990).

GLACIAL CLAYS

The vast majority of Minnesota is covered by varying thicknesses of Pleistocene glacial deposits. These surficial deposits belong primarily to the Wisconsin glaciation, which overlies glacial debris of older glaciations. The surficial

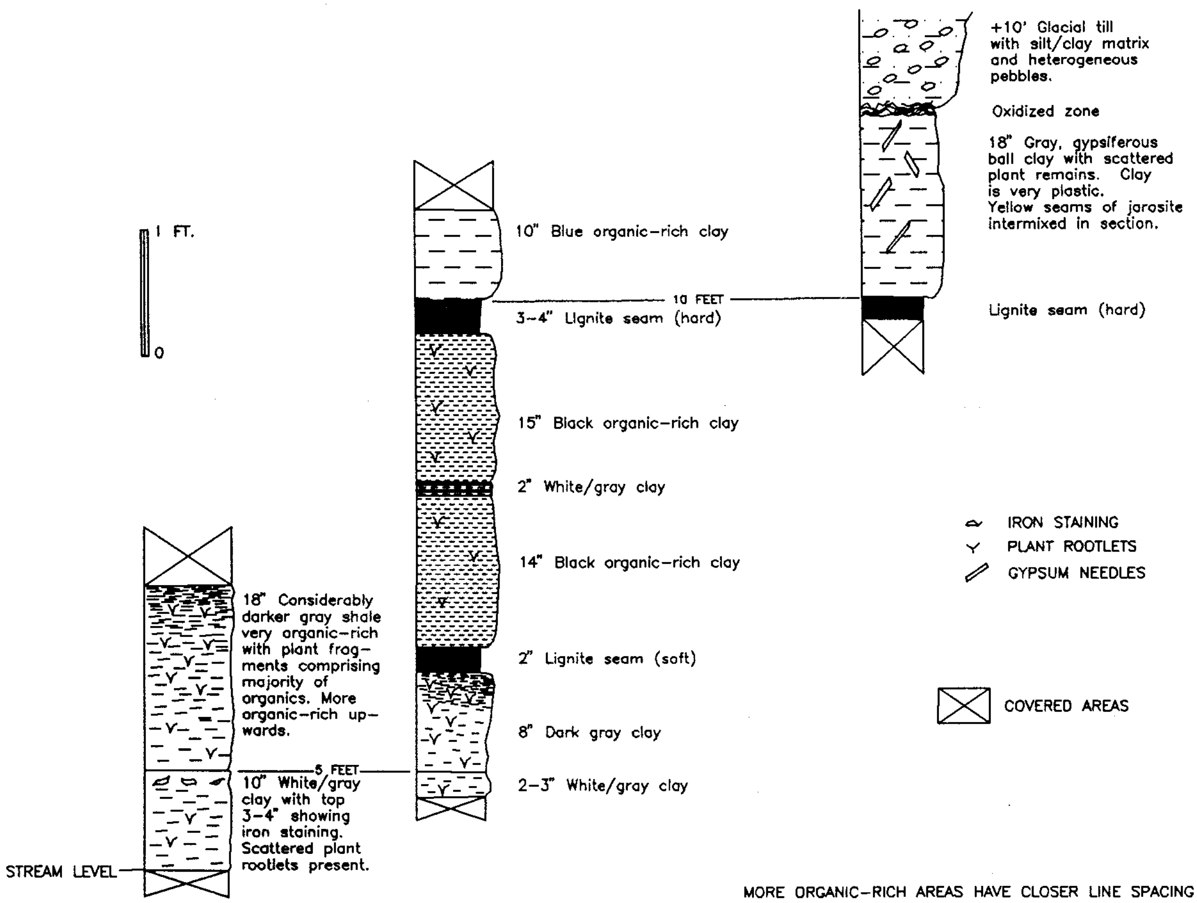

Figure 12. Late Cretaceous stratigraphic section, Richmond, Stearns County (after Toth and others, 1990).

glacial deposits in much of Minnesota are primarily composed of material deposited by the Des Moines and Superior lobes and various glacial lakes (Figures 13 and 14) and in north-central and northeastern Minnesota, by the Wadena and Rainy lobes. Also, loess deposits, that formed from fine-grained wind blown debris (Des Moines lobe), occur in the southeastern and southwestern portions of the state. The total thickness of these glacial deposits can be up to 400 ft. thick, but the cumulative thickness of these deposits is in the 5-100 ft. range. The glacial lake clays (Figure 14) were the primary source of brick making clays in the central and northern portions of Minnesota. Brickyards in Wrenshall in northeastern Minnesota produced bricks from glacial Lake Duluth sediments while brickyards in the western and northwestern parts of Minnesota used glacial Lake Agassiz sediments.

Bricks made from the glacial lake sediments generally fired to a cream or light red to salmon color. The glacial lake sediments are primarily composed of very fine-grained rock flour and a minimal amount of clay minerals. However, the offshore lacustrine clays of the Brenna and Sherack Formations in glacial Lake Agassiz (Harris and others, 1974; Arndt, 1977; Fenton and others, 1983) bloat upon firing at 1830° F (Hauck and others, in prep.) and may make excellent lightweight aggregate. The bloating of these clays may be due to dolomite and the presence of swelling clays. Carbonate is a major component of most glacial clays, especially those clays associated with the Des Moine Lobe, which contains a large percentage of Paleozoic carbonate-rich material.

RECENT CLAYS

Recent (since the retreat of the Wisconsin ice) clays were collected from lacustrine and river environments, in particular the Mississippi and Minnesota rivers. The largest use of recent river clays was in the extreme southwest portion of Minnesota in Rock County, where the clays (ca. 1890) were used to produce bricks for the four state area (Grout and Soper, 1919). Otherwise, these recent clays have had minimal usage as clay products, in part due to location on major waterways. The clay size fraction consists of illite and kaolinite with minor quantities of mixed layered clays.

GEOCHEMISTRY

Major element (SiO_2, Al_2O_3, TiO_2, Total Fe_2O_3, FeO, CaO, MgO, MnO, Na_2O, K_2O, P_2O_5, CO_2, H_2O, and S)

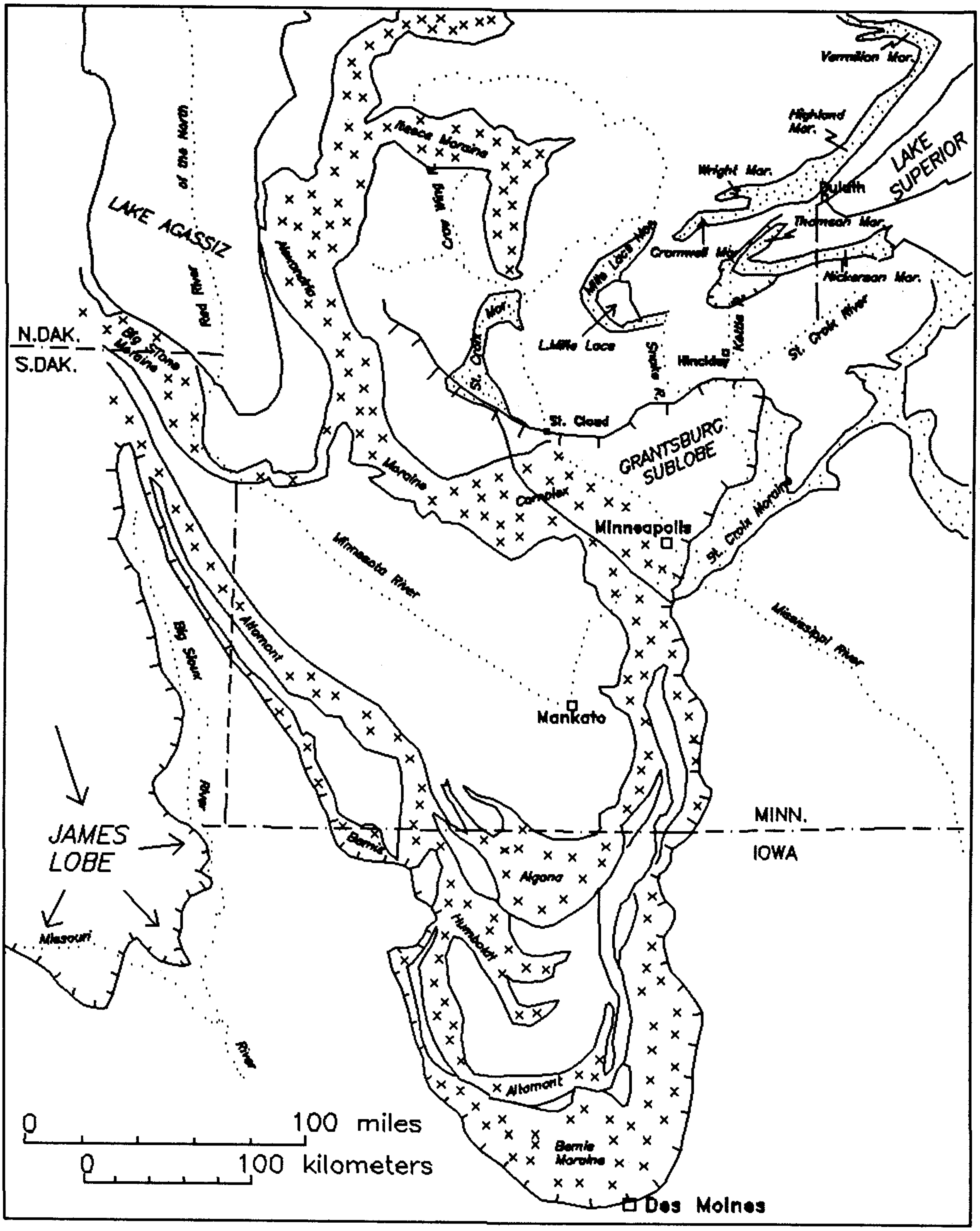

Figure 13. Distribution of Wisconsin tills (Des Moines and Superior lobes) in Minnesota (after Goldstein and others, 1987).

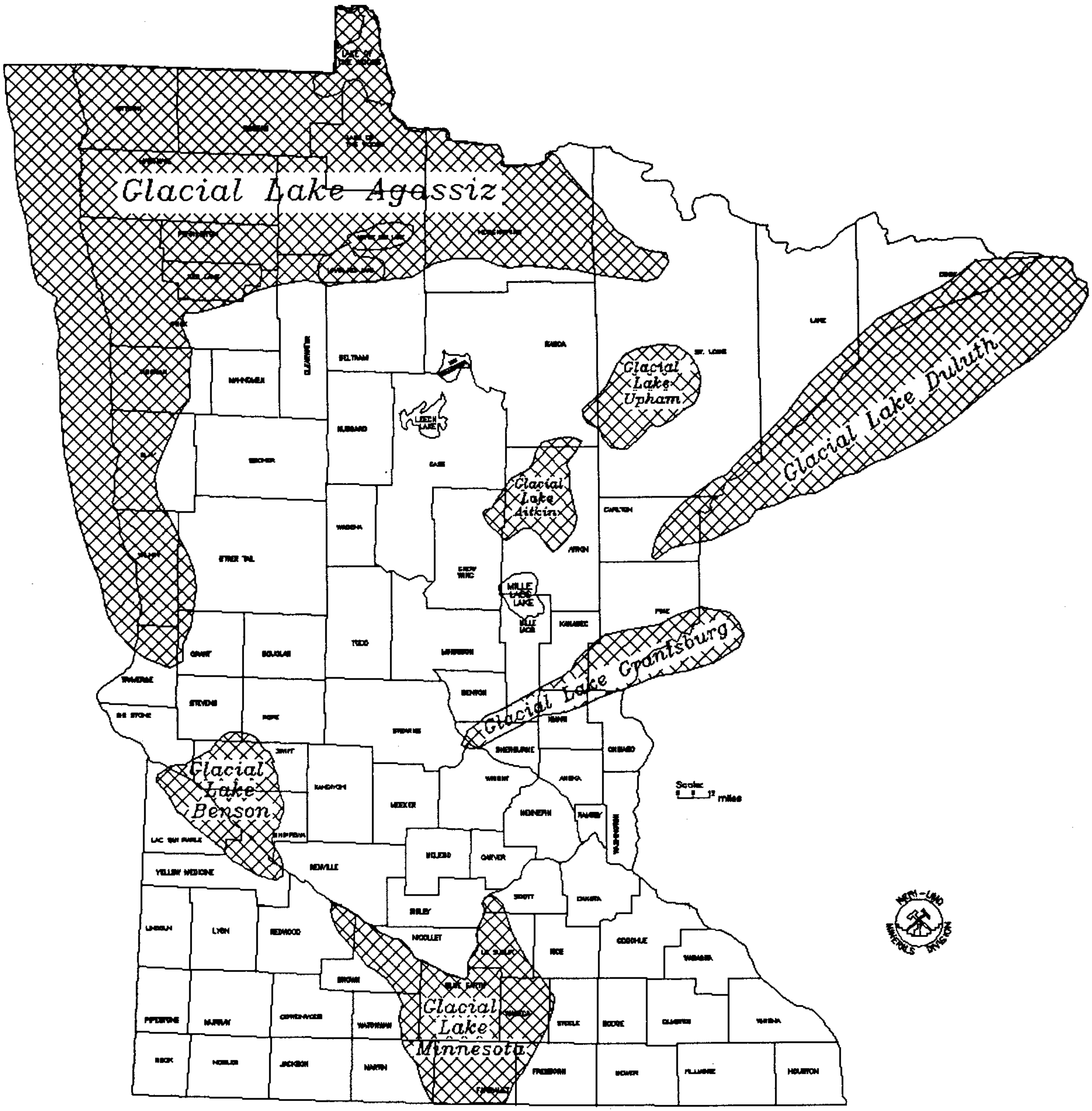

Figure 14. Location of glacial lakes in Minnesota (after Bray, 1977 and Diedrick and Rust, 1975).

geochemical analysis was conducted on 65% of the samples collected. Total organic carbon was also analyzed on those samples that contained organic material. The data presented in Figure 15 best represents the presence and distribution of clay minerals in the various types of clays.

In the residual clays, the Al_2O_3, TiO_2, and total Fe_2O_3 content decreases with depth, while SiO_2 increases. MgO, Na_2O, and K_2O also increase slightly with depth. The aluminum and titanium are concentrated near the paleoweathering surface due to their immobility during chemical weathering. TiO_2 is strongly correlated with Al_2O_3 suggesting that titanium is either retained in the kaolinite by substitution for Al or as discrete anatase and/or rutile particles (Newman and Brown, 1987).

The geochemistry of the secondary kaolinitic clays is controlled by the amount of quartz and kaolinite. With a decrease in the particle size, Al_2O_3 and TiO_2 increase and SiO_2 decreases (less quartz present). Again, TiO_2 has a strong correlation with Al_2O_3. MgO, Na_2O, and K_2O show no change when compared to residual kaolinitic clays, and these elements do not appear to be dependent on or related to particle size. The secondary kaolinitic clays contain from 1.5-2 times as much Al_2O_3 as the saprolite or residual clays (Figure 15). This relationship indicates that weathering and transportation of the residual clays have concentrated the kaolinite while removing other minerals, e.g., quartz, mica, etc. The K_2O and Na_2O content of the secondary kaolinite clays is less than in the residual clays, which also supports the weathering and reworking hypothesis.

The geochemistry of the Cretaceous sediments compared with the residual and secondary kaolinitic clays is similar. Both the geochemistry and the X-ray mineralogy, i.e., presence of kaolinite in both types of samples, suggests a common genetic association between the two clay types, i.e., weathering and reworking of the residual and secondary kaolinitic clays contributed to the composition of the Cretaceous sediments. This relationship is also substantiated by the white "porcelain" firing color of some Cretaceous shales and the higher Al_2O_3 content of shales that directly overlie secondary clay deposits. Yet, like many residual and secondary clays, the presence of secondary iron has contaminated many near surface deposits.

The geochemistry of the Paleozoic clays (Figure 15) supports the weathering origin for these clays as proposed by Parham and Austin (1969). The variation in these data may reflect the change in the illite/kaolinite ratio.

PHYSICAL CHARACTERISTICS

FIRING CHARACTERISTICS

To evaluate the ceramic potential of Minnesota's clays and shales, the firing characteristics of 194 samples were determined. Small test bricks of each sample were fired over a range of temperatures commonly encountered in the ceramics industry. Most samples were fired in the 1751° to 2381° F (cone 08 to 10) range, with selected samples fired as high as 2806° F (cone 19). The higher temperature firings were performed to assess a sample's refractory potential.

Shrinkage, 24-hour H_2O absorption and Munsell color were determined for each sample at each firing temperature. These properties are important because they can significantly influence a raw material's ceramic potential. The percent linear shrinkage (fired and total) and percent absorption were plotted against firing temperature for all fired samples. Plots for eight representative sample types are presented in Figure 16. The additional horizontal line at 8 percent on each plot marks the ASTM absorption standard for brick.

By plotting shrinkage and absorption in this fashion, the degree of "maturing" that takes place during firing becomes apparent. For example, increasing firing temperature usually results in increasing shrinkage (except for samples that bloat, indicated by decreasing shrinkage) and decreasing absorption. An approximate, but by no means exclusive, indication of "maturity" is the point on the plot where percent shrinkage and absorption intersect.

The firing characteristics of the major sample types can be summarized as follows: 1) residual and secondary kaolinitic clays tend to be refractory; they also exhibit lower shrinkage and higher absorption; 2) Paleozoic shales (Decorah and Glenwood) have low absorption values at lower temperatures; however, some have a tendency to bloat (Figure 16); 3) Cretaceous shales have the widest potential utility, based on their ability to fire over a broader (higher) range of temperatures than most Paleozoic and Pleistocene clays and shales; 4) Pleistocene materials, while widespread, frequently reach suitable absorption values only over a narrow temperature range; therefore, their practical use can be severely limited in applications that require lower absorption values.

PARTICLE SIZE

Particle size analysis was conducted on 480 samples. The particle size distribution for each sample was determined by using Stoke's law for the silt and clay size fractions (1000 ml graduated cylinder with water, a deflocculant, and a 10-20 gm sample) and by sieving for the sand sized material.

Figure 17 illustrates the average particle size range for the different types of clay collected during this investigation. The particle size distribution for some processed industrial clays is provided for reference (Figure 17A). Comparison of the average particle size distribution for the various types of clays suggests that: 1) the secondary kaolinitic clays have potential as filler and coating grade clays; 2) some Cretaceous clays have potential as ball clays; 3) most glacial tills consist of sand and silt with minimal clay size material, while the glacial lake clays are either silt- or clay-rich with minimal sand; and 4) the Ordovician clays are generally ≥60 % clay.

CATION EXCHANGE CAPACITY

A potentially important characteristic of a particular clay, especially in landfill applications, is the clays' ability to adsorb or exchange ions. Cation exchange capacity (CEC) is one measure of that ability. In general, the greater the CEC of a material, the greater its surface area, which promotes the sorption of sorbable wastes, including cations, anions and

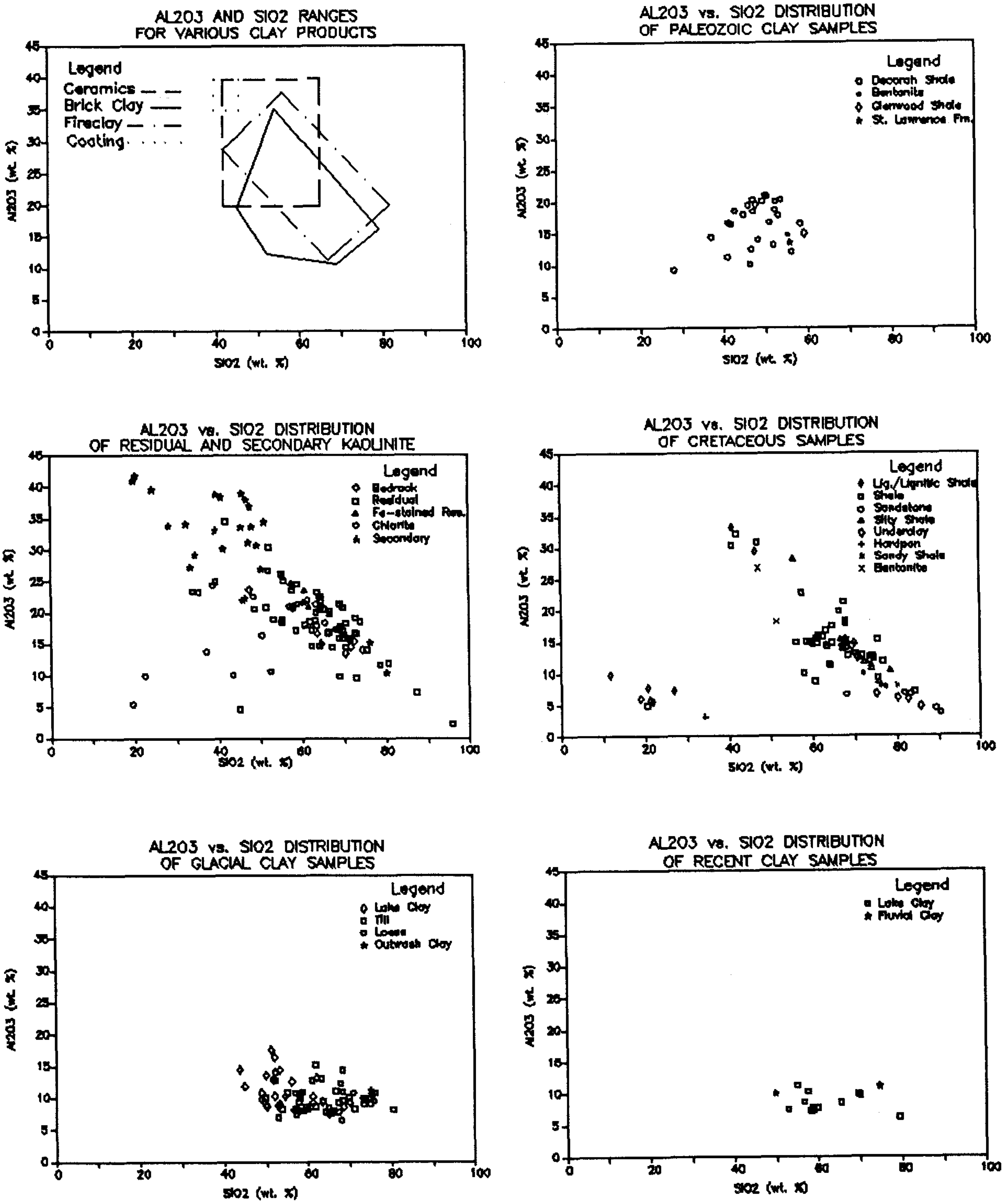

Figure 15. SiO_2 versus Al_2O_3 plot for each clay type in Minnesota.

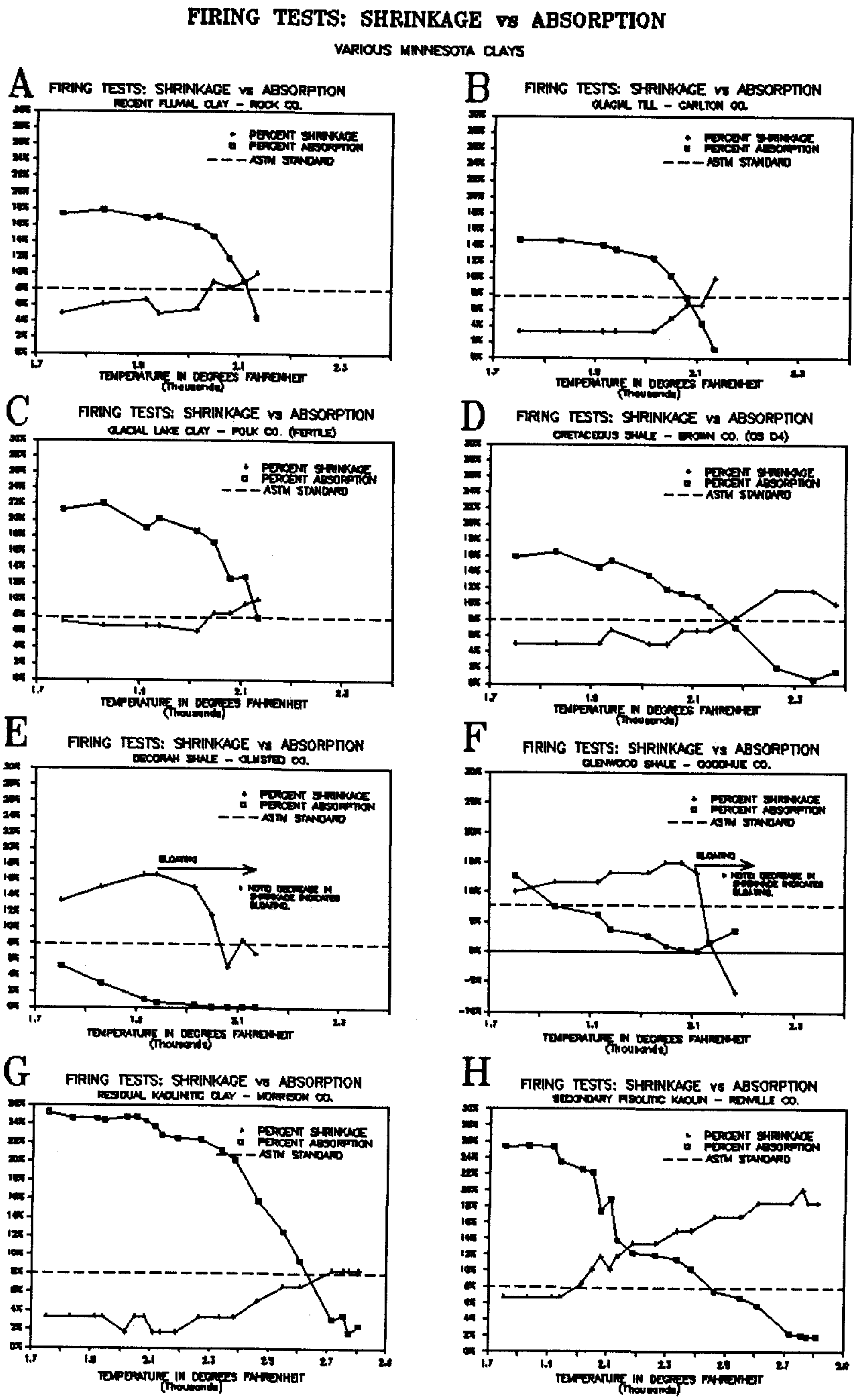

Figure 16. Representative shrinkage and absorption versus temperature diagrams.

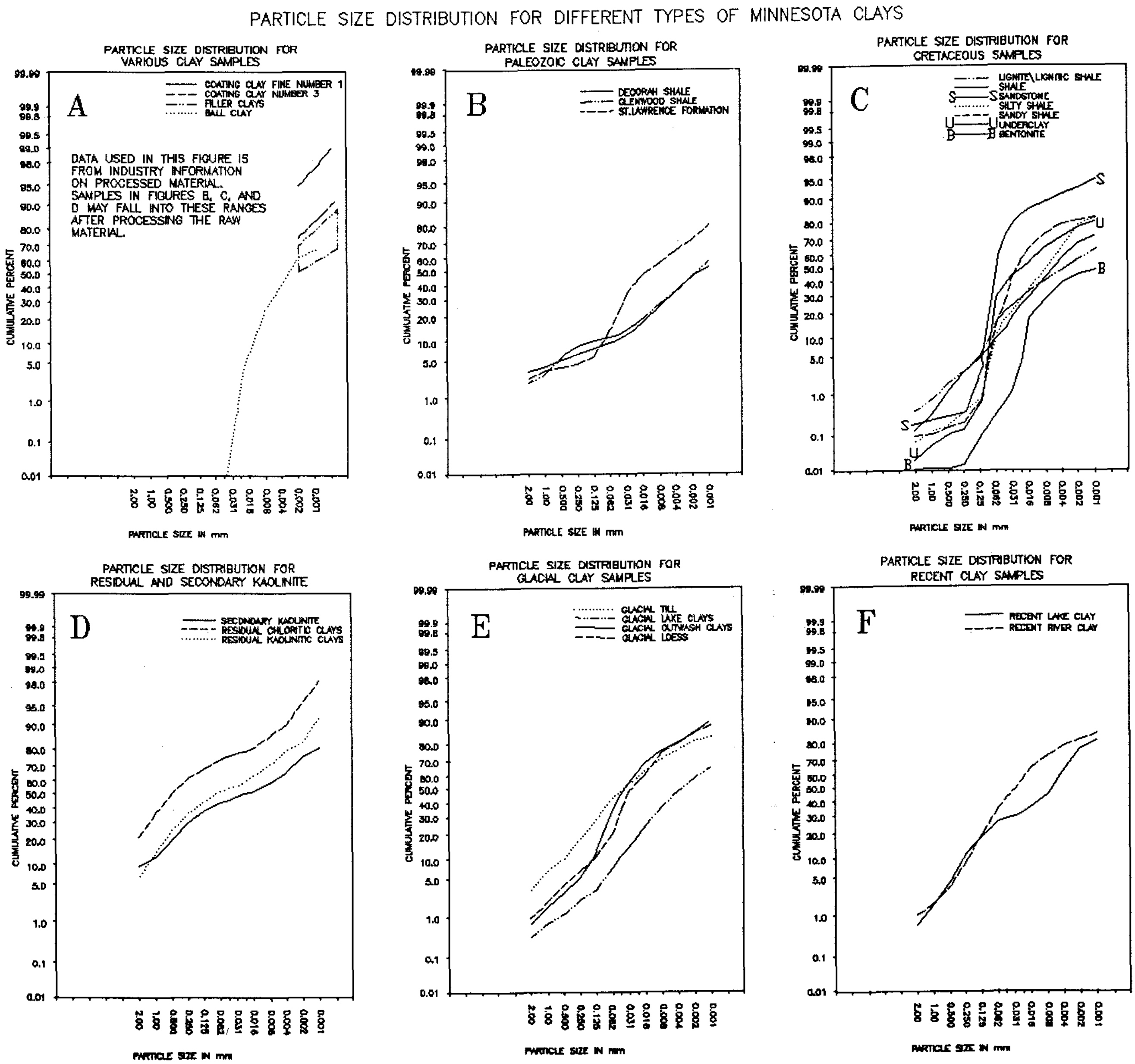

Figure 17. Particle size analyses for the various types of clays.

organics (Dawson and Mercer, 1986). The cation exchange capacity (CEC) of 493 samples was determined using the methylene blue test (American Petroleum Institute, 1988) that was modified by the Bureau of Mines (Haas and others, 1987). The methylene blue test provides an estimate of the total cation exchange capacity, or reactivity, of solids in drilling fluids. Since the solids of interest are generally clays, the test is applicable not only to drilling fluid clays (bentonites), but clays in general.

The highest CEC was obtained on the green bentonitic shale in the Ochs' Morton East pit (CEC of 50; Figure 8). Overall, the Paleozoic shales had the highest average CEC (12.5) followed by the glacial sediments (lake [12.4], loess [9.3], till [8.9], respectively), recent clays [7.8] and the residual and secondary kaolinitic clays [4.6-6.9].

SUMMARY

Many of these clays are currently being investigated for possible industrial uses, i.e., ceramic tile, lightweight aggregates, and livestock feed filler (Toth and others, 1990). Also, exploration for paper and filler grade kaolinite is presently underway in the Minnesota River Valley. The authors are currently conducting a regional mapping and sampling project to determine the chemical and fluvial/mechanical controls on the distribution and grade of the kaolinitic clays in the Minnesota River Valley. In addition, preliminary processing of some kaolinitic clays from the Firle property suggests that these clays can meet filler grade standards (Prasad and others, 1990).

Minnesota has a variety of clays that have not been or are not presently being used as an industrial mineral. Many of these clays have sufficient thickness, grade and homogeneity to support an ongoing operation, besides favorable physical and chemical properties. Possible uses for these clays are ceramic tile (glazed and unglazed), lightweight aggregate, refractory products, sanitary ware and fillers for livestock feed, plastics, etc.

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DEVELOPMENT AND POTENTIAL OF BEDROCK AGGREGATE RESOURCES OF NEWFOUNDLAND

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ABSTRACT

The demand for high quality aggregate, for use in concrete and road construction along the eastern seaboard of the United States currently exceeds supply. Development of new reserves in this densely populated region is difficult, due to environmental and municipal regulations.

Sources of bedrock aggregate to supply this market and others, are currently being developed in Newfoundland; one such operation has already begun production on the Port au Port Peninsula. In addition a study to assess the bedrock aggregate potential of Newfoundland's south coast is nearing completion. This project involved a detailed investigation of 131 sites, of which 23 show excellent potential for high-quality aggregate at tide water. The proximity of Newfoundland's south coast to both the United States of America and the European markets, and the low cost of shipping, suggest that there is excellent potential for additional development of aggregate resources.

INTRODUCTION

Sources along the eastern seaboard of the United States have been regularly importing aggregate for a number of years, which would indicate that the local producers do not have the necessary quantity of aggregate to supply local need. There are a number of reasons why aggregate quantity may be a problem in an area: lack of material, depletion of reserves, municipal boundary encroachment on reserves, environmental restrictions, etc.

Newfoundland's geographical position and the relatively low cost of shipping provides a competitive edge in the American and possibly the European markets. At present, Nova Scotia and Scotland are exporting high quality - bedrock aggregate to the United States markets. Newfoundland is currently being introduced to these markets with its Lower Cove development.

The production potential of Newfoundland should be considered on the basis of five important points:

(1) Favorable location to world markets as Newfoundland is ideally located and the distance to Florida and Great Britain are virtually the same.

(2) High-quality aggregate for concrete and road construction. Since 1985, rock samples have been collected from around the province and to date over 1200 samples have been retrieved. Initial geotechnical testing on these samples indicate that well over 70 percent are of high quality.

(3) Unlimited production potential. The south coast of the island has relatively high relief, which ranges from 100, to well over 1200 feet, and in some places reaches up to 1400 feet; these mountain ranges continue along the coast.

(4) Safe, deep, ice-free ports with tide water access. The south coast of the island, has numerous fiords and bays. It is ice-free all year round and tide water access is common all along the coast.

(5) Minimal land-use conflicts. The south coast is sparsely populated with only four communities on the coast, and has large areas of barren outcrop.

A reconnaissance study of the south coast of Newfoundland was initiated to find possible sites for bedrock aggregate potential, for export (Figure 1). The scope of the investigation consisted of collecting field-data, which involved the recording of any geological features which may be deleterious or beneficial to the rock.

These include:

(1) Faults
(2) Fractures
(3) Joints
(4) Folds
(5) Flow structures
(6) Bedding
(7) Grain size
(8) Alteration zones
(9) Mineralization
(10) Degree of weathering

Also, the laboratory investigation consisted of:

(1) Petrographic examination (ASTM C295-85)
(2) Magnesium Sulphate Soundness (ASTM C88-83)
(3) Los Angeles Abrasion (ASTM C535-89) (ASTM C131-89)
(4) Alkali-reactivity (ASTM C289-87)

Although the reconnaissance study is directed on the south coast of Newfoundland, a brief comment should be made on the Lower Cove quarry which is the only bedrock aggregate quarry for export in the province.

LOWER COVE

Lower Cove is situated on the Port Au Port Peninsula of the west coast of Newfoundland (Figure 2). It is a limestone quarry owned and operated by Newfoundland Resources and Mining Co. Ltd. The construction cost of setting up the operation was approximately 28 million dollars and the

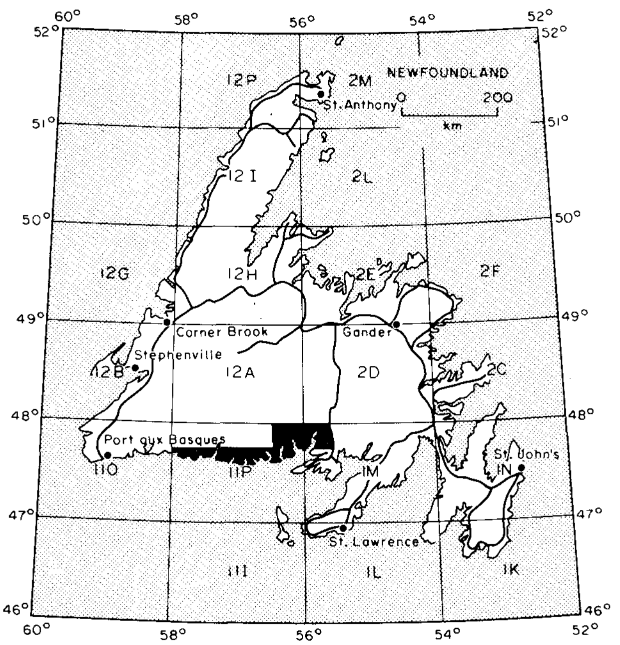

Figure 1. Location of the study area.

projected production per year is 4.2 million tons. Reserves for the site are estimated at 1,200 million tons, and the first shipment is expected this spring.

POTENTIAL AGGREGATE PRODUCTION IN NEWFOUNDLAND

The reconnaissance investigation was carried out to assess potential export aggregate sites on the south coast of Newfoundland. Due to the large area of the survey (Figure 1), only random sampling was carried out. From these sites, a number of areas (Long Harbour, Grole, McCallum, Cape La Hune, Grey River and Burgeo) (Figure 2) were chosen for consideration as potential sources for aggregate export.

LONG HARBOUR

The Long Harbour area, which is situated in Placentia Bay on the Avalon Peninsula, was chosen for consideration because of its docking facilities, large storage area, and it has a deep ice-free harbour. The bedrock passed all physical tests and there is unlimited production potential for the next 150-200 years.

The geology of the area consists of Cambrian sedimentary and volcanic rocks of the Big Head Formation, Musgravetown Group (King, 1988). The sedimentary rocks consists of fresh slightly weathered indurated fine to medium grained sandstone, siltstone and mudstone with minor conglomerate and shale. The rocks are generally fresh with minor iron-oxide surface weathering and localized deformation (cleavage).

The volcanic rocks consist of intermediate to mafic pyroclastics (tuffs and breccias) and vesicular basalts. For bedrock aggregate purposes the volcanic rocks are not suitable for concrete aggregate because of their potential for alkali-reactivity.

A total of 16 samples were collected, and of these 11 were considered to be of high quality, 4 of marginal quality and 1 of poor or low quality.

GROLE

Grole, situated on the Hermatage Peninsula, Newfoundland, was chosen because of its accessibility by road.

The general geology of the area consists of the Grole Diorite sequence which consists of dark grey quartz diorite to diorite, medium to coarse grained gabbro and numerous basic and silicic dikes.

A total of 3 samples were taken; 2 samples were considered to be of high quality and 1 sample of marginal quality.

MCCALLUM

McCallum, which is located on the south coast of Newfoundland has numerous deep bays and safe harbours.

The geology of the area consists of fine to coarse grained, K-feldspar, biotite granite. The granite locally contains a prominent foliation defined by aligned biotite and locally fattened quartz (Blackwood, 1985b).

A total of 8 samples were collected, 4 samples were considered to be of high quality and the remaining 4 samples of marginal quality.

CAPE LA HUNE

Cape La Hune, located on the south coast of Newfoundland has the same geographic features as the McCallum area.

The geology of the area consists of the Francois Granite which is a large unit and ranges from fine to coarse grained, feldspar porphyritic granite (Poole et al., 1985; Dickson et at., 1985). The fine to medium grained granite is usually fresh, hard and high quality locally, however the coarse grained granite ranges from marginal to poor quality. The granite at this site is exceptionally fresh and hard which would make this an excellent site.

A total of 13 samples were collected from this unit, of these 5 were considered high quality, 6 marginal and 2 samples of poor quality.

GREY RIVER

The geology of the area consists of the Grey River Enclave (Blackwood 1985a) which is a unit of mainly migmatized pelite, psammite schist, mafic schist, amphibolite and gabbro.

A total of 9 samples were collected, 7 were considered to be of high quality and 2 samples of marginal quality.

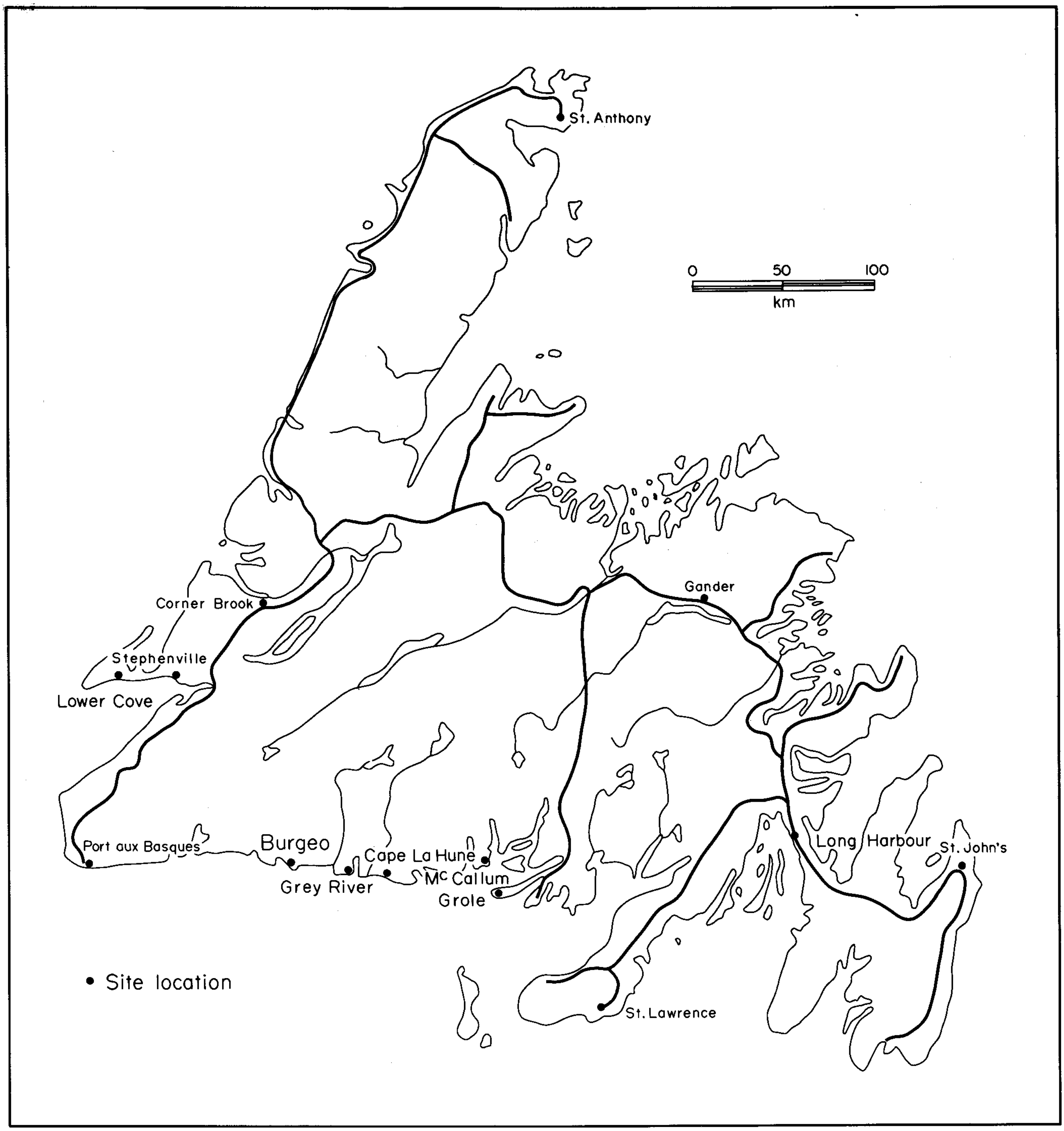

Figure 2. Site locations.

BURGEO

The geology of the area consists of the Burego Granite (O'Brien et al., 1986) which is a unit consisting mainly of coarse grained feldspar, biotite granite and granodiorite; however fine and medium grained granite zones may be found locally.

A total of 20 samples were collected, 7 are considered to be of high quality, 8 marginal and 5 samples are considered to be of poor quality.

RESULTS

Following the site investigation, an initial quality reference (petrographic number of P.N.) was given to each site on the following considerations. The rock types were rated on the basis of the amount of deleterious substances present and the petrographic number.

Deleterious substances are materials that occur in or on rocks and are capable of producing adverse effects; e.g., chemical reactions with other minerals resulting in a deterioration of the rock or cement binder used in concrete or asphalt. Some common deleterious substances include clays, organic matter, mica, iron and manganese oxide staining and cherty or fine grained siliceous material. alteration zones, encrustations and the degree of weathering are also factors considered to be delirious to the rock.

The petrographic number was calculated for each site and this measured the initial quality of material for aggregate purposes. The petrographic number is calculated by sampling 100 clasts or rock fragments and assigning a petrographic factor to each clast or fragment. The petrographic factors range from 1 (best) to 10 (worst) depending on rock types, weathering, and hardening. Each clast is given a petrographic factor of 1, 3, 6 and 10 (Canadian Standards Association, 1973; Table 1). A modified petrographic series of factors (from Bragg, 1986) is given in Table 2. These factors provide an initial assessment of the rocks for aggregate use. The petrographic number of a rock is the sum of the petrographic factors for 100 clasts or rock fragments and thus can range between 100 and 1000. The petrographic factor/number is usually affected by the degree of weathering (Table 3). Table 4 shows the petrographic number ranges of different rock units found in the study area.

Table 5 shows the initial assessment of the quality of the different rock groups based on field observations and petrographic number. The Burgeo, Francois and McCallum granites and the gabbros of the Grey River Enclave are all considered to be of high potential for concrete aggregate (Table 4) and should be investigated further. The majority of samples (50) came from these units, and 23 samples were considered to be of high potential (P.N. 110-130), 20 samples were considered to be marginal quality (P.N. 150-200) and only 7 samples, 5 of which were Burgeo granite, were considered poor quality (P.N. 215-300).

Of the 26 samples taken from the Bay d' Espoir metasediments and the Gaultois granite, only 1 sample of the metasediments is considered high quality (P.N. 110), 5 samples are considered marginal (P.N. 155-200) and the remainder 12 samples are considered to be of poor quality (P.N. 225-600).

Table 6 gives the results of detailed testing of representative samples from each group or formation.

CONCLUSION

With its geographic location, deep and ice free bays, unlimited production potential, minimal land use conflicts, low cost of shipping and results from initial and selective detailed testing shows the Newfoundland's south coast to be of high potential for concrete aggregate supplier for export.

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WEST VIRGINIA'S NONFUEL MINERAL RESOURCES

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INTRODUCTION

Nonfuel minerals are some of West Virginia's most important products. They are essential raw materials for the State's construction, chemical, manufacturing, agricultural, and mining industries. West Virginia's most significant nonfuel minerals, in order of tonnage produced, include limestone and dolomite, sand and gravel, sandstone, salt, and clay and shale. In 1988, about 15 million short tons of nonfuel minerals valued at about $150 million were produced in West Virginia.

GEOLOGIC SETTING

The geology of the state plays an important role in the type, availability, and location of West Virginia's nonfuel mineral resources. Most of West Virginia's bedrock is sedimentary except for small areas of igneous and metamorphic rocks in some of the extreme eastern counties. The State is divided physiographically by the Allegheny Front into two areas: the eastern Valley and Ridge Province and the western Appalachian Plateau Province (Figure 1). The Valley and Ridge includes older rock units from Cambrian through Mississippian age which outcrop as narrow northeast-southwest trending bands. The Appalachian Plateau is comprised of generally younger rock, Mississippian to Permian in age, which crop out as wide, arcuate bands subparallel to the Valley and Ridge outcrops. In general, all of the rock units thicken southward and eastward (Price and others, 1938). Quaternary alluvial and lake deposits occur in major stream valleys.

The eastern third of West Virginia is in the Valley and Ridge Physiographic Province (Figure 1). The Valley and Ridge is characterized by tightly folded and sometimes faulted structures eroded to subparallel valleys and ridges trending northeast- southwest. As a result of intense folding and faulting, beds commonly dip steeply and crop out as parallel belts of rock sequences which may be repeated several times. Ridges are generally capped by resistant sandstones, and the intervening valleys are of soluble limestones and easily eroded shales. The oldest units, Cambrian in age, are found in the easternmost counties in the Great Valley section of the Valley and Ridge. Ordovician, Silurian, Devonian, and Mississippian-age units crop out in the remainder of the Valley and Ridge.

The western two-thirds of West Virginia is in the Appalachian Plateau Province (Figure 1). Younger sediments of the Appalachian Plateaus were deposited in the Dunkard Basin over the older units now exposed in the Valley and Ridge. Rock strata are relatively flat- lying with a gentle regional dip toward the basin's center in northwestern West Virginia. A band of the oldest units of the Appalachian Plateaus, Mississippian limestones, sandstones, and shales, rim the basin's edge at the Allegheny Front. Farther west, Pennsylvanian cyclic sequences of sandstone, shale, clay, limestone, and coal deposited in deltaic and alluvial fan environments, crop out in a wide band that encompasses almost 50% of the State. In northwestern West Virginia, rock units similar to the Pennsylvanian sequences but with more shales and thinner limestones and coals are believed to be Permian in age.

The Allegheny Mountain Section of the Appalachian Plateau, located at the base of the eastern panhandle, includes structurally controlled open folds. Erosion of these open folds has exposed Mississippian and Devonian units in the midst of younger Pennsylvanian strata. As a result, economically important Mississippian limestones are exposed in northern West Virginia.

Quaternary alluvial and lake deposits also occur on many of the major rivers in West Virginia. The western border of the State , the Ohio River, contains up to 145 feet of sand and gravel outwash from Pleistocene glaciers in neighboring Pennsylvania and Ohio. The sand and gravel is located in nested terraces, floodplains, and in the river channel. Quaternary clay deposits also occur in the Ohio River Valley, the Monongahela and Potomac River valleys, and in the abandoned Teays Valley (Figure 1).

CONSTRUCTION AGGREGATE

Construction aggregate is West Virginia's major nonfuel commodity in terms of production value and tonnage. Of over 14 million tons of limestone, dolomite, sand and gravel, and sandstone quarried in the State during 1988, almost 11.5 million tons were processed for aggregate. That tonnage was valued at about $46 million, equalling almost one-third of the State's total value of nonfuel mineral production. Aggregate has a wide variety of applications in construction including use in concrete, asphalt, as railroad ballast, road base, and fill. Limestone and dolomite are West Virginia's leading construction aggregates followed by sand and gravel, and sandstone. Artificial construction aggregate produced in the State includes slag and ash from coal-fired power plants.

West Virginia can be roughly divided into three aggregate producing regions, based on geology. Ohio River sand and gravel is produced in the western part of the State; sandstone in the center; and limestone in eastern West Virginia. The type of aggregate used for a construction project partially depends on local geology because aggregate is a high-volume, low-value commodity that is expensive to transport. At

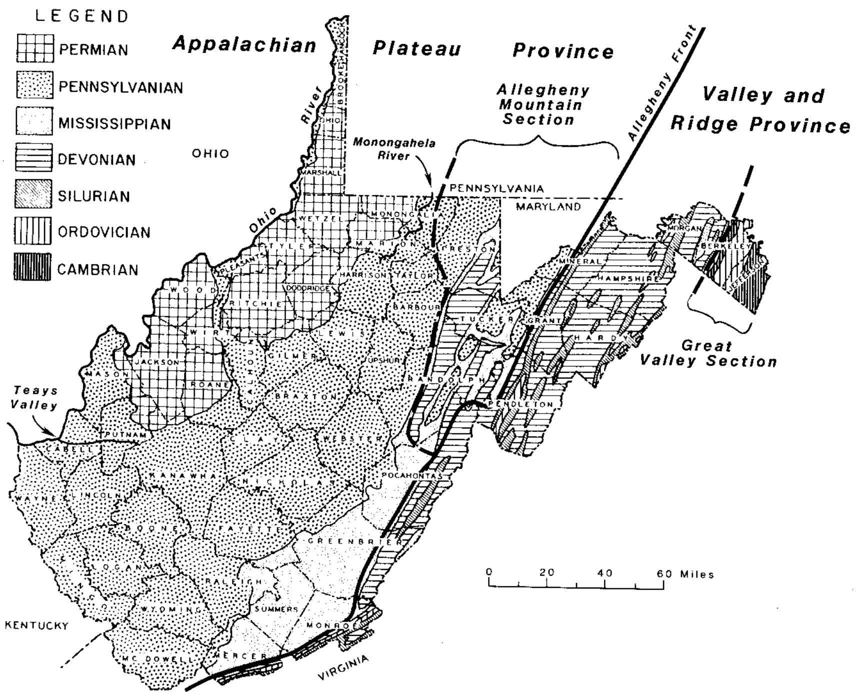

Figure 1. Generalized geologic map and physiographic provinces of West Virginia.

10 cents per ton per mile, trucking costs can exceed the value of the aggregate in a short distance. Most construction producers truck aggregate within a 50 to 75 mile radius of the production site in order to be competitive, but aggregate can be delivered farther if a construction project requires a specific type of material or if water transportation is available.

LIMESTONE AND DOLOMITE

Limestone and dolomite, West Virginia's most important nonfuel commodities constitute the State's primary construction aggregates. Of the approximately 11 million tons of limestone and dolomite produced in 1988, approximately 9 million tons were crushed and processed for construction aggregate (Simard and McColloch, in press). Total limestone and dolomite production in 1988 comprised 73% of the State's nonfuel mineral tonnage (Figure 2).

Limestone and dolomite are important because they are high quality aggregates, and because eastern West Virginia is endowed with several thick, areally extensive units of high-calcium carbonate limestone and high-purity dolomite. Limestones and dolomites in the Valley and Ridge commonly are steeply dipping and crop out as parallel belts of rock sequences (Figure 3). Two of the thicker units, the Mississippian Greenbrier Limestone and the Cambrian Tomstown Dolomite, are commonly greater than 1,000 feet thick (Price, and others, 1938). The Tomstown Dolomite is exposed only in Jefferson County. The Greenbrier Limestone crops out in many eastern counties and is thickest in the southeast. The Ordovician New Market, Chambersburg, and Saint Paul Group Limestones, which contain some high-purity dolomitic zones, are other important limestone sources for crushed stone. Ordovician limestones also crop out in several eastern counties.

West Virginia's largest nonfuel mineral producers are

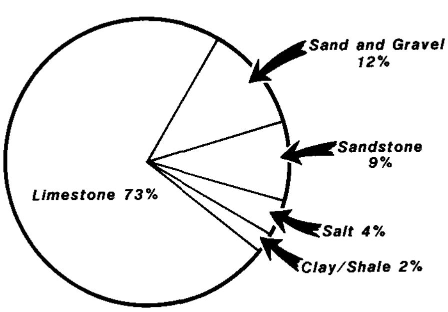

Figure 2. 1988 nonfuel mineral production.

limestone producers. In 1988, the three largest operations were Millville Quarry, Incorporated, producing 2.8 million short tons; Greer Limestone Company, producing 1.4 million short tons; and Capitol Cement Corporation, producing 1.2 million short tons. The two leaders produce crushed limestone aggregate, and the third produces cement from limestone and shale. In 1988, 27 of the 31 limestone operations were surface quarries; four operated underground mines. Fifty percent of limestone production in 1988 came from the Greenbrier Limestone; 43% from Cambrian Tomstown Dolomite and Ordovician New Market, Chambersburg, and Saint Paul Limestones; 7% from Devonian Helderberg Limestone, New Creek and Keyser Formations, and the Tonoloway Limestones; and less than 1% from thin Pennsylvanian Monongahela Group limestones.

Two quarries in Harrison County, located in north-central West Virginia, produced crushed stone from Monongahela Group limestones. These limestones have thin, irregular beds with numerous shale partings. As a result, the quarries are small and the product meets specifications for only a limited number of construction uses.

In western and central West Virginia, when the specifications of a construction project require limestone, it is either trucked in from the eastern part of the State or barged in from out-of-state sources. In a few areas of western and central West Virginia, subsurface folds have brought the Greenbrier closer to the surface, showing promise for shaft mining. The limestone is at least 100 feet thick (thick enough to be economically important), is with in 500 to 900 feet of the surface, and is near river/rail transportation and major markets (Welker, 1984).

Besides serving as the major aggregate source, l imestone is used for manufacturing cement, hydrated and pebble quick lime, limestone sand, agricultural limestone (aglime), coal mine safety dust, and other commodities produced in the State. Eastern West Virginia has several valuable high-calcium limestone and high-purity dolomites ranging in age from the Cambrian through the Mississippian.

Portland cement was the State's second leading nonfuel commodity in value in 1988 (Prosser and King, 1988). The only cement producer in West Virginia, Capitol Cement Corporation, ranks third in quantity of raŵ material produced in West Virginia. The quarry and processing plant are located in the Great Valley Section of the Valley and Ridge near Martinsburg, Berkeley County. The Ordovician Chambersburg and New Market Limestones and the Martinsburg Shale are quarried and manufactured on site into portland and masonr y cement. Another company, Lone Star Cement, mines the Greenbrier Limestone underground in Monongahela County but transports the raw material, by a combination of truck and barge, to Pittsburgh for cement manufacturing.

The Ordovician Saint Paul Group limestones in Pendleton County are quarried and processed into chemical grade products by Germany Valley Limestone Company, a subsidiary of Greer Steel Company. Pebble quick lime and hydrated lime are produced in rotary kilns near the quarry site. The pebble quick lime is sold as a water purifier, a flux, and refractory material for the steel industry. The hydrated lime is sold mainly for use in water treatment. Also produced at the quarry are limestone sand, coal mine safety dust, aglime, and on demand, crushed stone. The limestone sand is primarily sold for use in manufacturing glass and secondarily as concrete sand; coal mine safety dust is applied to underground coal mine walls to prevent explosions; and aglime is used in farming and mine reclamation.

Several other West Virginia quarries produce aglime from Cambrian through Mississippian limestones and dolomites. At present, Germany Valley Limestone Company is the only producer of coal mine safety dust in West Virginia, the state nationally ranked third for coal production. Later this year, R.B.S., Incorporated wil l be producing coal mine safety dust from the Greenbrier Limestone in Greenbrier County.

Great potential for increased limestone usage exists as a pollution control material for coal-fired power plants. Flue-gas desulfurization devices (e.g. scrubbers) and fluidized-bed combusters use limestone or lime as a sorbent to remove sulfur liberated by the combustion of coal prior to its release into the atmosphere. Currently, only two of West Virginia's 20 coal-fired power plants have emission control systems using limestone: one uses a fluidized-bed combustion system, the other uses a flue-gas scrubber system. Both power plants are located in the Ohio River Valley. Pending new legislation may encourage installation of scrubbers, thus increasing demand for limestone and lime.

SAND AND GRAVEL

Sand and gravel production followed limestone in quantity of nonfuel mineral raw material produced during 1988. At 1.8 million short tons, sand and gravel contributed approximately 12% to 1988's total nonfuel mineral tonnage production (Figure 2). The Ohio River, the western border of the State, was West Virginia's sole source of commercially produced sand and gravel in 1988. Small quantities of sand and gravel suitable for fill have been intermittently produced from other river channels. All of the Ohio River sand and gravel was used for construction aggregate.

The Ohio River Valley contains several nested terrace and floodplain deposits of Pleistocene and Holocene age alluvium. The deposits are attributed to outwash drainage of

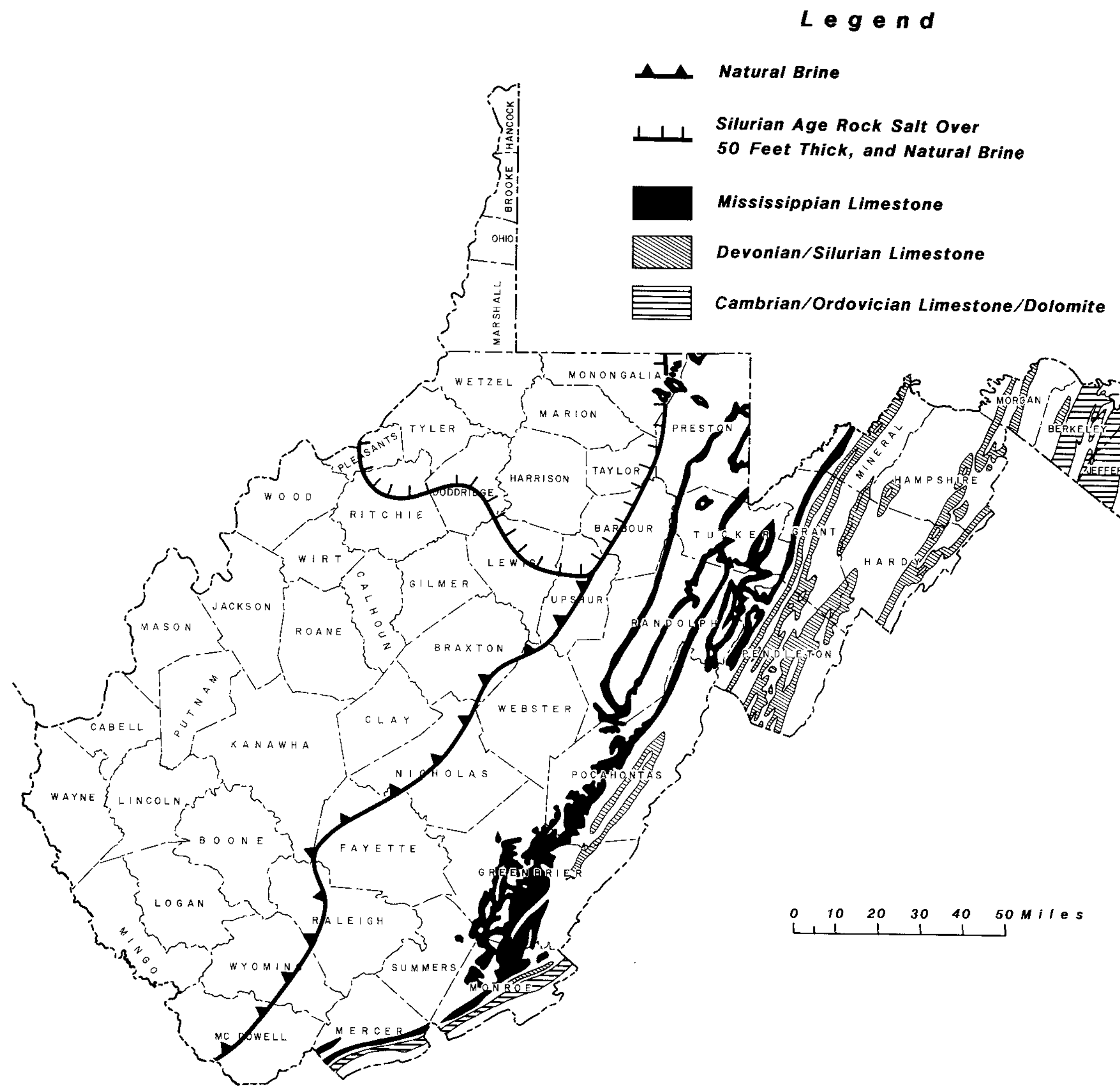

Figure 3. Limestone and dolomite outcrops, areas underlain by at least 50 feet of Silurian Salina Formation rock salt, and probable area underlain by natural brine in West Virginia.

the Late-Pleistocene Wisconsinan glaciers in Ohio and Pennsylvania. Terraces are composed of as much as 145 feet of lenses of interbedded sand and gravel, generally covered by less than 10 feet of either sand or silty clay. Floodplains consist of sand and gravel overlain by 10 to 30 feet of silty-clay floodplain deposits. Grain size and thickness of the sand and gravel terrace deposits decrease downstream, whereas valley width increases downstream (Simard, 1989).

Ohio River sand and gravel is an excellent construction material because of its glacial and alluvial origin. The sand and gravel includes metamorphic and igneous rock and well-cemented sandstones not found in western West Virginia. These rock types, more durable and frost-resistant than local sedimentary rock, make better concrete. They were also well-washed and well-rounded during their transportation process. In contrast, alluvium from local streams has a large percentage of fines and is composed of poorly- rounded and poorly-cemented sandstones that are often shaly.

Ohio River sand and gravel is obtained from terraces and dredged from the river channel. Two-thirds of West Virginia's 1988 sand and gravel production was dredged from the river channel. Dravo Corporation dredged the channel in Ohio and Brooke Counties in the northern panhandle; further south, Pittsburgh Sand and Gravel, Incorporated dredged the channel in Marshall, Tyler, and Pleasants counties.

The remaining one-third of the 1988 sand and gravel was produced from terraces by Shippingport Sand and Gravel Company (now a subsidiary of Lafarge Corporation) in Hancock County, the State's northernmost county. Kelley Sand and Gravel, Incorporated, and two other companies produced sand and gravel in Mason County, in southwestern West Virginia. In the recent past, smaller commercial quarries produced sand and gravel from terraces along the length of the Ohio. The deposits are also excavated locally with a backhoe for fill and skid-resistance grit by city and county highway departments and land owners. Commercially produced sand and gravel is either trucked within a 50 mile radius of the operation or shipped by river barge to more distant areas.

SANDSTONE

Sandstone, a widely available source for construction aggregate, is primarily quarried in central West Virginia. Most of the State's sandstone aggregate is produced from abundant Pennsylvanian sandstones of the Appalachian Plateau, but it is also produced from an older unit in the Valley and Ridge. Crushed sandstone is an important aggregate for central West Virginia because it is used in the region's extensive coal mining and reclamation, and oil and gas drilling industries, and by cities and towns for construction. Although eastern limestones and western sand and gravel are consistently of better quality than aggregate produced from many of the sandstone units, transportation costs into the area can quickly exceed the value of the aggregate.

In 1988, 12 sandstone quarries produced about 650,000 short tons of aggregate, approximately 5 percent of the total nonfuel mineral production. The greatest amount was produced from southern and eastern areas of the Allegheny Plateau where Pennsylvanian sandstones are massive, thick, and of higher quality than in the rest of the State. Almost half of the tonnage was produced in Raleigh County by Raleigh Stone Company from the Upper Raleigh Sandstone, and Beckley Stone Company from the Lower Nutall Sandstone (both of the Pottsville Group).

The next three largest producers, each producing between 100,000 and 50,000 tons annually, quarried the thick Penns ylvanian Conemaugh and Pottsville Group sandstones in Preston, Tucker, and Logan Counties. In the Valley and Ridge Province, a small quarry in Grant County produced less than 10,000 tons of aggregate during 1988 from the extremely hard Silurian Tuscarora Formation. The remaining sandstone aggregate producers are in central West Virginia where the Pennsylvanian sandstones are thin, discontinuous deltaic and alluvial fan deposits with numerous shale partings. In 1988, each produced less than 10,000 tons each of relatively poor quality aggregate suitable for fill or road base.

West Virginia's sandstone is equally as important for high-purity silica sand production as it is for construction aggregate. Minor amounts of sandstone are also quarried in the State for dimension stone. The Devonian Oriskany (Ridgeley)Sandstone, composed of well- sorted, well-rounded grains of at least 98% silica, is of excellent quality for the glass industry. U.S. Silica Company, the State's sole producer of silica sand, operates a quarry near Berkeley Springs, Morgan County. Their annual production tonnage is approximately equal to the State's sandstone aggregate production. U.S. Silica processes the Oriskany (Ridgeley) Sandstone into silica sand, ground silica, and micron-sized silica mainly for use by the glass industry. The ceramics, electronic parts, and paint industries, to name a few, also purchase specialty silica sand from the Morgan County operation. In the past, the Pennsylvanian Homewood, Connoquenessing, and East Lynn Sandstones, and the Silurian Tuscarora Sandstone were also quarried for glass sand.

Dimension stone, more important in the past than now, is currently produced in minor amounts for facing as a sideline to sandstone aggregate. Mazella Quarries, Incorporated, located in Kanawha County near Charleston, produces hand-hewn facing from the Pennsylvanian-age East Lynn Sandstone. Many of the State's high- quality sandstones of all ages have been quarried in the past for use as dimension stone.

ARTIFICIAL AGGREGATE

Artificial construction aggregate includes slag (a byproduct of steel making), and fly ash and bottom ash (coal-fired power plant waste). Slag from the Weirton Steel Company in Weirton, Hancock County, is sold for construction aggregate of comparable quality to sand and gravel and crushed stone. One company processes steel slag whereas two other companies process iron blast-furnace slag. Steel slag can be used in road base, in asphalt, and as fill. Iron blast-furnace slag has the same uses as steel slag and can also be used in concrete.

Fly ash can be substituted for sand and cement in concrete products. West Virginia's 20 coal-fired power plants, located primarily in the western half of the State, produce large amounts of fly ash. Considerable research and promotional effort on use of fly ash as a construction material has been conducted in the past 20 years. In West Virginia, this material has been used in road construction, power plant construction, and in concrete block for several West Virginia University buildings.

SALT

West Virginia has enormous salt resources in deep rock salt beds and in natural brines. Most of northwestern West Virginia is underlain by greater than 50 feet of rock salt of the Silurian Salina Formation (Figure 3). Depth from the surface to the top of the Salina varies from approximately 5,000 feet by the Ohio River at Chester, Hancock County, to 9,000 feet at Morgantown, Monongalia County (Martens, 1943). The Salina Formation consists of layered beds of salt, limestone, dolomite, and anhydrite. The individual salt beds are never much more than 100 feet thick and the greatest cumulative thickness of salt in one place is 240 feet in Monongalia County (Smosna and others, 1977). To the south and east, the Salina Formation grades into limestone and shale.

Commercial development of the Salina Formation has occurred along the Ohio River where the salt beds both attain maximum thickness and are closest to the surface. Current salt production is in Marshall County (at the base of the northern panhandle) by PPG Industries, Incorporated and LCP Chemicals-West Virginia. Both companies solution-mine the top salt bed which is about 100 feet thick (Martens, 1943). Solution mining is the technique of pumping fresh water down a well into the salt formation and pumping the salt-saturated solution to the surface for processing. Both companies produce caustic soda and chlorine which are marketed to the plastic, pulp and paper, metal fabricating, petroleum refining, and rubber reclaiming industries (Prosser and King, 1988).

Natural brine underlies the western half of the State especially in the Silurian Tuscarora Formation, the Devonian Oriskany Formation, the Mississippian Greenbrier Limestone and Pocono Group, and the Pennsylvanian Pottsville Group (Price and others, 1937). Salt production from brines from salt springs in Kanawha County was the first mineral industry in the State. Later wells were drilled all over western West Virginia to reach deeper brines. Commercial production of the natural brine continued to boom until World War II when the deep Salina salts were discovered and tapped. Abundant natural brine resources remain.

CLAY AND SHALE

West Virginia has extensive clay and shale resources distributed throughout the State. Principle types of clay/ shale deposits that have been or are presently mined include shale formations, coal seam underclays, and Quaternary lake and river clays. In 1988, West Virginia had three clay/shale producers whose combined tonnage contributed 2% to West Virginia's total nonfuel mineral production (Figure 2). Analyses of Statewide samples of the different types and ages of clay and shale deposits show great potential for use in many ceramic products including light weight aggregate (Lessing and Thomson, 1973). The tests have shown that some Ordovician through Permian clays and shales have potential for use as expanded aggregate.

The Ordovician Martinsburg Shale is one of the State's economically important shale formations. The Martinsburg Shale is exposed in the folded strata of the Valley and Ridge as steeply dipping northeast-southwest trending belts (Figure 1). The formation outcrop, occurring only in the State's eastern border counties, ranges in thickness from a few hundred to 1,500 feet thick . The most extensive outcrops occur in the eastern panhandle in Jeffe rson and Berkeley Counties. Currently, the Martinsburg Shale is quarried near the town of Martinsburg, Berkeley County, for raw material used in manufacturing cement and brick. Capitol Cement Company quarries the Martinsburg Shale and Ordovician limestones to produce portland and masonry cement.

Continental Brick Company is the State's remaining pro ducer of a once-thriving West Virginia brick industry. Continental Brick produces face brick used for buildings of all types. Their main market is the Washington and Baltimore area but brick is shipped as far as Minnesota, New York, and Virginia. Outcrops of Devonian shale of equal or greater thickness than the Martinsburg Shale satisfactorily test for use in sewer pipe, building brick, face brick, and lightweight aggregate (Lessing and Thomson, 197 3).

Smaller Pennsylvanian and Permian age shale units have been historically important raw materials for brick and structural clay products. Although they are ubiquitous in the Appalachian Plateau, the flat-lying individual shale units are thinner and less continuous than the thick Ordovician or Devonian shales. Thickness of Pennsylvanian and Permian shales range from a few feet to about 50 feet. In the past, shale deposits of this age were used in manufacturing many kinds of products including different kinds of tile, paving block, sewer pipes, and brick.

Coal seam underclays (commonly called fireclays) are another important, widespread resource in West Virginia. Underclays of minable thickness occur in association with many of the State's Pennsylvanian and Permian coal seams. Currently, the Penns ylvanian Bolivar Fire Clay is quarried by the Sanders Dummy Company in Lincoln County, southern West Virginia. The fireclay is ground into a powder and shaped into clay dummies (the size and shape of a stick of dynamite) for use in spacing explosive charges in blast holes. Sanders sells the dummies by the truckload to another company for resale to coal mines. Several different underclays have historical significance in the production of numerous types of clay products including refractory brick, paving brick, face brick, tiles, sewer pipes, and pottery.

Quaternary alluvial and lake clays also have historical economic importance. Production has occurred from the Lake Monongahela clays (produced primarily along the Monongahela River), clays from the Ohio River Valley and some of its tributaries, and the abandoned Teays River Valley lake clay. These deposits were used by the once-thriving pottery, earthenware, and chinaware industries. Today, only independent potters locally use Quaternary deposits for their craft. Great potential exists for use of these Quaternary clays.

SUMMARY

West Virginia's nonfuel minerals are vital to the State's economy. They are essential raw materials for a wide variety of applications in the construction, chemical, manufacturing, and coal mining industries of the State and surrounding areas. Their total production value annually exceeds $125 million. Great potential exists for further utilization of the vast quantity and high-quality nonfuel mineral resources of the State.

The West Virginia Geological and Economic Survey has a number of products and services available to assist individuals, companies, and governmental agencies in determining location, quantity, and quality of the State's nonfuel mineral resources. Anyone interested in our publications, open-file reports, maps, data files, knowledge, and experience on the nonfuel minerals of West Virginia can contact us. We will be happy to serve you.

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ABSTRACTS

THE ROLE OF THE U.S. BUREAU OF MINES IN THE DEVELOPMENT AND REGULATION OF INDUSTRIAL MINERALS

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For years, the United States Bureau of Mines has been the principal agency of the federal government charged with the responsibility of collecting, analyzing, and disseminating information on over 100 mineral commodities, half of which are industrial minerals. Many of these minerals are ubiquitous in the industrial economy, but all are basic raw materials vital to major sections of our domestic economy. With an ever-increasing growth in population and urban development, growing concern for rebuilding of the nation's infrastructure, major shifts in material requirements for changing manufacturing and chemicals industries, and an increased focus on the environment, the issues surrounding industrial minerals have never been greater. The Bureau of Mines will continue to play a major and proactive role in addressing these issues and in fostering a sound domestic minerals industry.

OVERVIEW OF DEPARTMENT OF MINES, MINERALS AND ENERGY REGULATORY PROGRAM FOR METAL/ NON METAL NOMENCLATURE

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The Commonwealth of Virginia, through the Department of Mines, Minerals and Energy maintains a staff of 24 Division of Mineral Mining personnel to regulate the safety, health and environmental impact of metal/nonmetal mines. This includes the certification training for mine foremen and blasters. Permits issued by this Division must be obtained by industry prior to any mining activity. Operational/development plans must be filed with a permit application addressing the safety and environmental issues for the proposed mining operation. The subject matter of this plan may include hydrologic impact, geologic structure of the deposit and any inherent safety concerns, grading plans including storm surface runoff management, mine maps, hazardous material handling, and the proposed post-mining land use. The permit process can also includetheholding of public hearings concerning any application.

Accidents occurring at mining operations involving medical treatment, lost time, serious injury or fatality are investigated by Division staff. Regulations concerning ground control, fire prevention, air quality, explosives, mobile equipment, personal protection, electricity, and materials handling have been adopted. These regulations are enforced through regular inspections made by Division personnel.

This Department also administers a state program, unique in the nation, for abandoned metal/non-metal mines. Funds are available to correct safety and environmental hazards left by mining operations prior legislation to cover these responsibilities. The priority of reclamation projects is determined by an Orphaned Land Advisory Committee staffed by representatives of various state agencies, state universities, citizens, and the mining industry.

NORTH CAROLINA INDUSTRIAL MINERALS: COMMODITIES, APPLIED MINERAL RESEARCH, REGULATION, AND RESOURCES TO ASSIST MINERAL DEVELOPMENT

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North Carolina is richly endowed with and produces a significant amount of industrial minerals. These include clays, feldspar, gemstones, mica, peat, sand and gravel (construction and industrial), stone (crushed and dimension), talc and pyrophyllite, lithium minerals, olivine, and phosphate rock. Production was $584 million for 1989. North Carolina ranked 19th nationally in the output of all minerals and 11th in industrial mineral sales. The State continues to lead the nation in the output of feldspar, mica, olivine, pyrophyllite, and lithium (spodumene) and in 1989 ranked second in the production of common clay, crushed granite, and phosphate rock according to the U.S. Bureau of Mines.

Resources for mineral exploration and beneficiation are diverse. The state geological survey provides basic geologic information. It has a sample repository which includes drill core, cuttings, and geophysical borehole records. The contents of the repository are computer-based to make information retrieval easier. The geological survey has a modern heavy mineral laboratory.

The North Carolina Department of Commerce and Economic Development and the Governor's office provide information on business development. The Minerals Research Laboratory, located in Asheville, can perform a wide variety of mineral dressing and pilot plant studies. The

State's geographic information service has extensive digital data which is useful for siting and for environmental impact studies.

Regulation is governed by the Mining Act, which requires that a mining permit be obtained for operations larger than one acre. The Land Quality Section of the Division of Land Resources administers the act. Also, air and water quality permits are required from the Division of Environmental Management.

Applied minerals research is active in North Carolina. Selected projects of the North Carolina Geological Survey include: high-silica resources of the Chilhowee Group (western North Carolina); heavy mineral investigations in the Fall Zone (in conjunction with planned regional geologic mapping beginning in late 1990); evaluation of aeroradiometric anomalies for heavy minerals in the Inner Coastal Plain; and offshore heavy- and industrial-mineral assessment in state waters. The Minerals Research Laboratory is working on a number of industrial-minerals beneficiation projects.

Significant economic reserves of ilmenite-bearing sands in upland sediments along the Fall Line in North Carolina have been discovered. At least eight exploration companies are actively exploring and delineating this resource. These terrace deposits are located primarily in Northampton, Halifax, and Wilson Counties. In addition to ilmenite, other minerals of potential economic worth include leucoxene, rutile, monazite, and zircon.

A geochemical atlas of the State is in preparation. The geochemical atlas is based on the National Uranium Resources Evaluation (NURE) data. The atlas is possible because North Carolina has nearly complete statewide sampling from that program.

The North Carolina Geological Survey is an affiliate office of the Earth Science Information Center (ESIC) which provides free searches of available aerial photography. The data set is maintained on CD-ROM to provide rapid client response. Orthophotographs are available at nominal cost. Topographic maps are not sold but a comprehensive map reference collection is maintained. A publication list is available upon request.

U.S. GEOLOGICAL SURVEY'S MINERAL RESOURCES DATA SYSTEM

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The U.S. Geological Survey (USGS) has been compiling and using the Mineral Resources Data System (MRDS) for nearly 20 years. The MRDS consists of a minerals site file, thematic data files, and public information reference files. It serves as an essential repository of metallic and industrial minerals deposit and occurrence information for use in mineral-resource assessments, national and international, and as a source of mineral information for the public.

The MRDS data is collected and used as an essential building block in USGS mineral-resource studies and assessments. The MRDS data base supports National Mineral Resource Assessment Program (NAMRAP) activities, including regional and state-wide studies and assessments; land management agency studies and assessments for administrative units such as national forests and wilderness study areas; and quadrangle-sized studies and assessments, often in cooperation with State geological surveys. MRDS data is also collected and used in USGS-assisted studies and assessments in foreign countries.

Throughout its history, the MRDS has been a source of mineral information for the public. This role was enlarged in 1988 when the USGS opened the first of four Mineral Information Offices to provide walk-in facilities for the mineral community and the general public. These offices feature the MRDS in a user-friendly graphics environment; this is the same system that is available for viewing at this meeting. The Mineral Information Offices provide an opportunity for us to work directly with the public. The creation of these offices has stimulated our development of graphics capabilities and thematic graphics data sets to enhance access to and the interpretation of the mineral-resources information available through the MRDS.

More MRDS users also means more scrutiny and feedback concerning its data. We recently instituted a comprehensive data quality assurance initiative, which includes installation of a series of data completeness and accuracy checks and the designation of a MRDS data editor to coordinate data-quality assurance and data-gathering activities.

The MRDS mineral sites file currently includes 85,000 site records. Although in the past the emphasis for MRDS data gathering has been focused on metallic mineral resources, and since the early 1970s on strategic and critical minerals, a considerable number of records contain information on industrial mineral deposits and occurrences. Increased gathering of industrial minerals information reflects our growing awareness of the importance of this sector of the minerals industry.

DEVELOPMENTS AND OPPORTUNITIES IN INDUSTRIAL CARBONATES ON NEWFOUNDLAND'S GREAT NORTHERN PENINSULA

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White, high purity marble deposits with potential for use as premium grade industrial filler have been identified on the Great Northern Peninsula by the Newfoundland Department of Mines. The marble occurs along a metamorphosed belt of Lower Ordovician carbonate rocks that structurally underlie the Hare Ray Allochthon. The high degree of purity and brightness of the marble, and its proximity to deep water ports have attracted the attention of developers. Current activities include diamond drilling and bulk sample testing.

The Lower Ordovician, carbonate platform rocks of the Great Northern Peninsula also host large deposits of dolomitic and limestone. Preliminary tests on dolomite near Port aux Choix and Cape Norman show that it may be of metallurgical grade. The carbonate sequences also host large deposits of limestone on tidewater that have yet to be assessed.

DIMENSION STONE IN NEWFOUNDLAND

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Exploration for dimension stone in Newfoundland and Labrador is on the upswing. There are no commercial operations at present, but megacrystic pink granite tiles were recently installed at the new Earth Science building at Memorial University in St. John's, and interest in the availability of this stone has followed. Considerable effort has been directed towards locating a suitable quarry site in a large body of fine-grained gabbro, a "black granite" virtually identical to the South African "Britts Blue". Examination of a variety of pink, red, green and grey granites, as well as black and white marbles, continues. In Labrador interest is focused on medium- to coarse-grained anorthosites composed of chatoyant labradorite crystals.

Despite intermittent production over the last 140 years, renewed development of the province's high quality slate reserves is now imminent. Current negotiations are aimed at a re-development of an old slate quarry at Nut Cove, and the development of a new quarry at Keels. Both of these deposits occur in the Cambrian aged slate in Eastern Newfoundland, which hosts green, purple, and red slate deposits.

1991 FORUM ON THE GEOLOGY OF INDUSTRIAL MINERALS: ALBERTA/BRITISH COLUMBIA, CANADA

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The 27th Forum on the Geology of Industrial Minerals will be held in Banff, Alberta, Canada in early May of 1991, hosted jointly by the provinces of Alberta and British Columbia. Banff, an internationally famous resort town in the Canadian Rockies, adjoins regions of both provinces richly developed in industrial mineral resources. The meeting will comprise two days of technical sessions and two field trips to visit some unique mineral operations in each province. The first field trip is a one-day excursion in the Bow Valley region of Alberta, scheduled between the two days of talks. The second is a two-day trip following the talks (with an optional one-day extension), in the East Kootenays region of British Columbia.

The Bow Valley trip will visit operations representative of Alberta's major industrial mineral products; sulphur, limestone (cement and lime), and aggregate. Sulphur extraction from natural gas is conducted at Shell Canada's Jumping Pound gas plant, where 600 tpd are recovered from sour gas produced from Mississippian reservoir strata at depths below 2950 m (9000 ft.). This plant is one of more than 50 that make Alberta the world's leader in sulphur production from hydrocarbon sources. Limestones are quarried by Lafarge Canada Inc. and Continental Lime Ltd. for cement and lime production respectively. The quarries are uniquely developed in scenic mountain settings, in steeply dipping beds of Devonian and Mississippian carbonate formations. Lafarge's plant site at Exshaw is also the location of the calcining facility for Baymag's magnesite quarry production in British Columbia. The aggregate operation of Burnco Ltd. is a major-scale working of alpine outwash gravels, which are 65+m (200+ ft.) thick in the Bow Valley and are depositionally unique. Another possible stop is a small stone quarry which produces "Rundlestone", the characteristic building stone of Banff (including Banff Springs Hotel-the Forum meeting site).

The East Kootenays trip will focus on several of British Columbia's important industrial mineral products: magnesite, silica, gypsum, limestone/dolomite, and dimension stone. Magnesite is quarried by Baymag Mines Co. Ltd. from a huge deposit at Mount Brussilof, the largest and purest magnesite deposit known in North America. Host unit is the Middle Cambrian Cathedral Formation, a thick (370 m) dolomite unit in which magnesite forms massive lenticular beds up to 100 m thick. Silica quarrying occurs at two localities near Golden, in the Ordovician Mount Wilson Quartzite. Mountain Minerals Ltd. quarries a friable phase of the quartzite formation for processing into a glass-grade silica sand. Bert Miller Construction Ltd. quarries massive quartzite for a lump silica product. Gypsum is quarried by Westroc Industries near Windermere and by Domtar Construction Materials near Canal Flats. Both quarrying operations are in strongly disturbed, steeply dipping beds of the host evaporite unit, the Devonian Burnais Formation, giving rise to some spectacular gypsum exposures.

An optional extension to the East Kootenays trip will examine limestone/dolomite fine-grinding operations near Creston, where International Marble and Stone Company produces white calcium carbonate filler and various crushed and sized white rock products, from Lower Cambrian limestone and dolomite formations quarried in the area. also in the area, Kootenay Stone Center quarries a Lower Cambrian quartzite for use as flagstone. The return journey through Crowsnest Pass to Calgary includes a possible stop at Summit Lime Works' unique quarrying and vertical kiln operations.